SOURCES AND EFFECTS OF IONIZING RADIATION

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ANNEX B

EXPOSURES OF THE PUBLIC AND WORKERS FROM VARIOUS SOURCES OF RADIATION

CONTENTS

INTRODUCTION

1. The exposure of human beings to ionizing radiation from natural sources is a continuing and inescapable feature of life on the earth. For most individuals, this exposure exceeds that from all man-made sources combined. There are two main contributors to natural radiation exposures: high-energy cosmic ray particles incident on the earth's atmosphere and radioactive nuclides that originated in the earth's crust and are present everywhere in the environment, including the human body itself. The world population is also exposed to radiation resulting from releases to the environment of radioactive material from man-made sources, and from the use of fuels or materials containing naturally occurring radionuclides. In addition, there are a wide variety of situations in which people at work are exposed to ionizing radiation. These situations range from handling small amounts of radioactive material, for example in tracer studies, to operating radiation-generating or gauging equipment, to working in installations of the nuclear fuel cycle. There are also situations where the exposure of workers to natural sources of radiation is sufficiently high to warrant the management and control of radiation as an occupational hazard. All these exposures were regularly assessed in previous reports of the Committee, the most recent being the UNSCEAR 2000 Report [U3]. The purposes of these assessments are to improve the understanding of global levels and temporal trends of public and worker exposure, to evaluate the components of exposure so as to provide a measure of their relative importance, and to identify emerging issues that may warrant more attention and scrutiny.

2. This annex comprises three sections. Section I addresses general issues related to dose assessment for public and occupational exposure to radiation, and the special quantities for measuring and assessing exposure due to radon. Sections II and III address the exposures to ionizing radiation of the general public and of workers, respectively. The distinction between public and occupational exposure is kept for two main reasons: *(a)* the two groups exhibit significant differences with respect to age, the numbers of people exposed, the relevant exposure pathways, and the methodologies for monitoring and assessing radiation doses;[1] and *(b)* there is a difference in responsibilities for managing the protection of workers and of the public that is reflected in the different interests of users of this annex.

3. This annex supplements and updates previous UNSCEAR publications on the subject. The estimates of radiation exposure have been based primarily on the submissions to the UNSCEAR databases for assessment of doses to the public and workers, supplemented by significant reports in the open literature. The annex does not cover processes previously described in detail; whenever pertinent, reference is made to sources where more detailed information may be found. In particular, because the Committee has separately evaluated exposures due to radon (annex E of the UNSCEAR 2006 Report [U1]), to medical uses of radiation (annex A of the 2008 Report) and to accidents (annex C of the 2008 Report), in particular exposures due to the 1986 Chernobyl accident (annex D of the 2008 Report), these aspects are not dealt with extensively in this annex. Where appropriate, summaries of other evaluations have been reflected here for completeness.

4. The Committee has historically described the exposure of members of the general public to the several different natural and man-made sources of radiation. The principal objectives of the analysis of public exposures presented in section II are:

- To evaluate the radiation levels worldwide to which human beings are usually exposed;
- To assess the usual variability of exposure worldwide to different sources;
- To identify sources of concern for public exposure;
- To allow users to derive benchmarks for comparison purposes, to manage exposures and to derive relationships for their investigative work;
- To analyse temporal trends in the contributions of different sources to overall public exposure.

5. It is often not straightforward to differentiate between normal exposures and enhanced exposures to natural sources of radiation, and between these and exposures to man-made sources. An illustrative example is the common assessment of radiation exposure indoors, where the natural background radiation exposure is influenced by the presence of natural radioactivity in building materials, leading to what are sometimes treated as enhanced exposures. Another example is the impact of the urbanization process, which is known to alter natural background radiation exposure (e.g. the laying of pavement reduces exposure from radionuclides in the soil,

[1] While doses to workers are mostly measured, doses to the public are usually assessed by indirect methods, typically using measurements performed in the environment or of environmental samples, modelling various exposure scenarios and employing data on population habits. The accuracy of assessments made usually differs with the methodology used: doses assessed for workers are normally more accurate than those for members of the public. Moreover, doses from occupational exposure relate to a specific set of people, usually healthy adults. Although assessments of doses to the public sometimes take account of the properties of different age groups or their specific habits, the values of the dose estimates do not usually apply to any specific individual within the population under consideration, but rather represent an average dose to groups of people.

whereas the use of granite and certain ceramic materials in the construction of buildings may enhance exposure). In addition, especially for developing countries, the expansion of industries (e.g. a new mining installation in an area with high levels of background radiation) may enhance public use and habitation of an area as new infrastructure becomes available, leading to changes in public exposure. Because of these difficulties, no attempt will be made here to draw a rigorous distinction between normal and enhanced exposures to natural sources of radiation. Subsection II.A, on public exposure to natural sources of radiation, includes consideration of exposures to cosmic and terrestrial sources of radiation.

6. The exposure of the general public to radiation resulting from industries deemed non-nuclear—such as the mining, milling and processing of ores that, apart from the raw material, contain uranium (U) and/or thorium (Th)—is described in subsection II.B on enhanced sources of radiation. Exposures resulting from nuclear industries (i.e. those related to the nuclear fuel cycle and to artificial radionuclides) are described in two subsections on public exposure to man-made sources. The first of these, subsection II.C, describes public exposure to man-made sources arising from peaceful uses of atomic energy (including energy generation and the operation of the associated fuel cycle facilities, the production of radioisotopes, the transport of nuclear and radioactive material, waste management and the use of consumer products). The second, subsection II.D, presents the public exposures to man-made sources related to military purposes (including atomic weapons tests and their fallout or radioactive residues, the military use of depleted uranium in war situations and sites contaminated by waste from previous practices, mostly associated with the development of nuclear weapons technology, but not including the exposures due to the Hiroshima and Nagasaki bombings). As doses received by the world population due to nuclear explosions have been described systematically in previous reports of the Committee and a major overview was presented in the UNSCEAR 2000 Report [U3], only a summary regarding the tests and the resulting worldwide exposures has been included here for completeness.

7. In section III the Committee has updated its evaluations of occupational exposures [U3, U6, U7, U9, U10] for work in six broad categories of practice: practices involving elevated levels of exposure to natural sources of radiation; the nuclear fuel cycle; medical uses of radiation; industrial uses of radiation; military activities; and miscellaneous uses of radiation (which includes educational and veterinary uses).

8. The Committee has evaluated the distributions of annual individual effective doses and annual collective effective doses resulting from occupational radiation exposures in the various practices or due to various types of source. The principal objectives of the analysis of occupational exposures remain, as in the previous assessments of the Committee, as follows:

- To assess annual external and committed internal doses and cumulative doses to workers (both the average dose and the distribution of doses within the workforce) for each of the major practices involving the use of ionizing radiation;
- To assess the annual collective doses to workers for each of the major practices involving the use of ionizing radiation. This provides a measure of the contribution made by occupational exposures to the overall impact of that use and the impact per unit practice;
- To analyse temporal trends in occupational exposures in order to evaluate the effects of changes in regulatory standards or requirements (e.g. changes in dose limits and increased attention to ensuring that doses are as low as reasonably achievable), new technological developments and modified work practices;
- To compare exposures of workers in different countries and to estimate the worldwide levels of exposure for each significant use of ionizing radiation.

9. According to the International Labour Organization, the formal definition of occupational exposure to any hazardous agent includes all exposures incurred at work, regardless of source [I62]. However, for radiation protection purposes, in order to distinguish the exposures that should be subject to control by the operating management from the exposures arising from the general radiation environment in which all must live, the term "occupational radiation exposure" is often taken to mean those exposures received at work which can reasonably be regarded as the responsibility of the operating management [I7, I16, I47]. Such exposures are normally also subject to regulatory control [I7]. The exposures are usually determined by individual monitoring, and the doses assessed and recorded for radiological protection purposes.

10. The terms "practice" and "intervention" have been widely used in radiological protection. The term "practice" has been used for human activities that increase the exposure or the likelihood of exposure of people to radiation or the number of people exposed. The International Commission on Radiological Protection (ICRP) had distinguished between "practices" that increase exposure or likelihood of exposure and "interventions" that reduce exposure or likelihood of exposure [I7, I47]. However, the latest ICRP recommendations [I60] use a situation-based approach to characterize the possible situations where radiation exposure may occur as "planned", "emergency" and "existing exposure" situations. The ICRP now believes that it is more appropriate to limit the use of the term "intervention" to describe protective actions that reduce exposure, while the terms "emergency" or "existing exposure" will be used to describe radiological situations where such protective actions to reduce exposure are needed [I60]. In this annex the terms "practice" and "intervention" are applied according to the previous ICRP definitions [I47].

11. The procedures for the recording and inclusion of occupational exposures differ from practice to practice and country to country, and this may influence the

respective statistics in different ways. Some countries may overestimate the size of the exposed workforce, and thereby distort assessment of the individual and population dose distributions. Moreover, some countries report only the doses of workers in controlled areas, while other countries report the doses from both exposed and non-exposed workers. Some countries do not adequately track the doses to contract workers, who may work and accumulate exposure in different industries, possibly even in different countries. These issues are discussed in subsection III.A. These differences in monitoring and reporting practices mean that caution must be applied in interpreting the reported data.

12. Although most workers involved in practices that are subject to controls established by the national regulatory authorities are individually monitored on a routine basis, there are a significant number of workers exposed to ionizing radiation who are not individually monitored. The largest proportion of these workers are those exposed to natural sources of ionizing radiation. Before the implementation of the International Basic Safety Standards for Protection against Ionizing Radiation and for the Safety of Radiation Sources (the "International Basic Safety Standards") [I7], few data were recorded in national databases on occupational exposure to natural sources of radiation. Recently, however, exposures to enhanced levels of natural radiation have become a focus of attention in the field of radiation protection. Subsection III.B is devoted to natural sources of occupational radiation exposure.

13. Subsections III.C and III.D address occupational exposure to man-made sources of radiation used for peaceful and for military purposes, respectively.

I. DOSE ASSESSMENT ISSUES

14. The basic quantity used here to describe radiation exposure is the "effective dose". Although this artificial quantity was developed strictly for protection purposes, it is used here for the purposes of exposure assessment. The annual committed effective dose includes the sum of external and internal doses and is usually reported in millisieverts (mSv):

$$E = E_{ext} + E_{\text{int}} \qquad (1)$$

15. The ICRP [I60] has very recently recommended new values for some of the radiation and tissue weighting factors in the definition of effective dose. However, for the evaluations here, the assessment of effective doses has been made on the basis of the earlier definition provided in ICRP Publication 60 [I47].

16. In particular, the Committee continues to use in its estimations of effective dose a radiation weighting factor (w_R) of 1 for all photon and beta emitters, including tritium. A recent report of an independent Advisory Group on Ionising Radiation to the Health Protection Agency (HPA) in the United Kingdom recommended that the ICRP consider increasing this value for tritium from 1 to 2 [A3]. The ICRP has considered this recommendation, taking into account recent reviews of the scientific basis for this value [L18, L19]. It concluded that, for assessments covered by their broad approach, i.e. that are not individual-specific, a value of 1 remains appropriate [C32].

17. In order to compare the total radiation dose from various sources incurred by different groups, the Committee uses the quantity "collective dose", which is defined as the sum of all the individual effective doses received in the group under consideration. It is expressed in units of man-sieverts (man Sv) [I7] and is accompanied by the number of individuals in the group. While this quantity was also developed strictly for the purposes of optimization of protection, it is used by the Committee to assess the relative importance of various sources of radiation exposure. The collective dose received by a group divided by the number of individuals in the group is the "average per caput dose" in this group.

18. The Committee uses the International System of Units to report data as values that can be easily used and recalled; specifically, it uses multiples and submultiples of the standard units, designated by the following prefixes:

peta	(P)	10^{15}	femto	(f)	10^{-15}
tera	(T)	10^{12}	pico	(p)	10^{-12}
giga	(G)	10^{9}	nano	(n)	10^{-9}
mega	(M)	10^{6}	micro	(μ)	10^{-6}
kilo	(k)	10^{3}	milli	(m)	10^{-3}

A. Public exposure

19. It is very rare that doses to members of the public are directly measured. Usually these doses are assessed on the basis of environmental or effluent monitoring data, using models to simulate environmental exposure scenarios. These scenarios and models have been extensively discussed in the UNSCEAR 2000 Report [U3], and only a summary of the most relevant aspects will be presented here.

20. The estimation of E_{ext} in Eq. (1) depends on the data available from environmental measurements. The main quantity used to characterize external exposure fields due to

natural sources is the absorbed dose rate in air, usually reported in nanograys per hour (nGy/h). Some authors report the air kerma, also expressed in nanograys per hour. Under the assumption that charged-particle equilibrium exists within the volume of material, the air kerma and the absorbed dose in air may be assumed to be equivalent. The factor used to transform measurements of absorbed dose in air to external effective dose to adults is 0.7 Sv/Gy, as described in the UNSCEAR 2000 Report [U3]. When describing public exposure, external exposures are assessed using effective dose rates expressed in units of either nanosieverts per hour (nSv/h) for instantaneous exposure fields, or millisieverts per year (mSv/a) for estimating the average annual exposure of individuals. The "occupancy fraction", related to the fraction of time spent indoors, I_{in}, and the "shielding factors" of buildings, *SF*, describing the ratio of the absorbed dose rate indoors to the absorbed dose rate outdoors, are also used to estimate average annual effective doses:

$$E_{ext} = 0.7\, D \quad [(1 - I_{in}) + SF \cdot I_{in}] \qquad (2)$$

21. External doses may also be estimated from environmental concentrations of natural radionuclides in soil, C_{soil}, using appropriate dose conversion factors, DCF_{soil}, as presented in table 1:

$$E_{ext} = C_{soil}\ DCF_{soil}\ [(1 - I_{in}) + SF \cdot I_{in}] \qquad (3)$$

22. Internal doses for adults are calculated using the 50 year committed effective doses (i.e. the integrated internal dose received over the 50 years following intake); for children, the committed effective doses are integrated up to the age of 70 years. Very few assessments include estimates of doses to children. Internal doses to members of the public are usually estimated on the basis of the scenarios described in the UNSCEAR 2000 Report [U3], using data on concentrations of radionuclides in the environment, such as concentration in water or food, C_k, expressed in becquerels per litre (Bq/L) or becquerels per kilogram (Bq/kg), and concentration in air, C_{air}, expressed in becquerels per cubic metre (Bq/m^3):

$$E_{\text{int}} = E_{inh} + E_{ing}$$

where

$$E_{inh} = \sum_j e_{j,inh}\ I_{j,inh} \quad = \sum_j \quad C_{j,air}\ e_{j,inh}\ IR_{inh}$$

$$E_{ing} = \sum_j e_{j,ing}\ I_{j,ing} \quad = \sum_{k,j} \quad C_{k,j}\ e_{j,ing}\ IR_k \qquad (4)$$

where *j* refers to radionuclides, *k* refers to the type of food or water, *I* is the intake of radionuclide, *IR* is the inhalation rate or the ingestion rate of foodstuff *k*, and *e* is the coefficient for conversion from intake to committed effective dose, $e_j(50)$, i.e. the committed effective dose integrated for 50 years for adults, and $e_j(70)$, i.e. the committed effective dose integrated up to the age of 70 years for children, separately for inhalation and ingestion. The dose conversion coefficients used in this annex for adults for doses due to intakes of natural radionuclides are also presented in table 1.

23. To assess doses due to the operation of nuclear power plants and other fuel cycle facilities, the dose conversion coefficients derived in the UNSCEAR 2000 Report [U3] have been used. These coefficients are specified in terms of the collective effective dose per unit release of a radionuclide. They are presented in table 2 for nuclear reactors and in table 3 for reprocessing facilities. For other fuel cycle facilities, collective doses have been estimated on the basis of the electrical energy generated and the same dose coefficients as used in [U3], namely 0.2 man Sv/(GW a) for operational uranium mining, 0.0075 man Sv/(GW a) for operational tailings piles, 0.00075 man Sv/(GW a) for releases from residual tailings piles, 0.003 man Sv/(GW a) for uranium enrichment and fuel fabrication facilities, and 0.5 man Sv/(GW a) for the disposal of low- and intermediate-level waste. The Committee has decided not to extend its estimates of doses into the far future, as was done in previous reports, because of the very large uncertainty inherent in such assessments. Thus only current doses received by members of the public are described in this annex.

24. For the assessment of exposures due to military uses of radiation, the main quantity used is also the effective dose, although sometimes the equivalent dose to specific organs, such as the thyroid, have also been reported. Both quantities are expressed in units of millisieverts, but when the term "dose" refers to a specific organ dose, this is made clear in the text. In this section, estimates for doses occurring in the past, present and near future are given. The future doses are mainly related to possible or predicted exposures due to the use of contaminated sites.

B. Occupational exposure

25. The ICRP, in its Publication 60 [I47], indicated that three important factors influence the decision to undertake individual monitoring: the expected level of dose or intake in relation to the relevant limits; the likely variations in the doses and intakes; and the complexity of the measurement and interpretation procedures that make up the monitoring programme. Where doses are consistently low or predictable, other methods of monitoring are sometimes used, as in the case of aircrew for whom doses can be calculated from flight rosters. The complexity of measurement techniques results in an approach to monitoring for external irradiation that is different from that for intakes and the resulting committed dose.

26. The estimate of the effective dose, *E(t)*, needs to take into account the contribution from external and internal exposure, if appropriate. *E(t)* can be estimated using the following expression:

$$E(t) = H_P(d) + \sum_j e_{j,inh}(50) I_{j,inh} + \sum_j e_{j,ing}(50) I_{j,ing} \qquad (5)$$

where $H_p(d)$ is the personal dose equivalent during time period t at a depth d in the body (normally 10 mm for penetrating radiation); $e_{j,inh}(50)$ is the committed effective dose per unit activity intake by inhalation of radionuclide j, integrated over 50 years; $I_{j,inh}$ is the intake of radionuclide j by inhalation during the time period t; $e_{j,ing}(50)$ is the committed effective dose per unit activity intake by ingestion of radionuclide j, integrated over 50 years; and $I_{j,ing}$ is the intake of radionuclide j by ingestion during time period t. Uptake through the skin and wounds can occur in some circumstances. For most forms of intake, the dose coefficients provided by the ICRP are for intakes by inhalation and ingestion and do not take into account uptake through the skin.

27. The United States National Council on Radiation Protection and Measurements (NCRP), in collaboration with the ICRP, has developed a biokinetic and dosimetric model for radionuclide-contaminated wounds. The multicompartment model uses first-order linear biokinetics to describe the retention and clearance of a radionuclide deposited on the wound site. Seven default categories have been defined to describe wound site retention: four relate to contamination with initially soluble materials (weak, moderate, strong and avid), and three relate to contamination with materials having solid properties (colloid, particle and fragment). The wound model is coupled to the ICRP systemic models for predicting urinary and faecal excretion patterns, as well as for producing wound-specific dose coefficients. However, the resulting dose coefficients are not yet available, and therefore the doses estimated in this annex were based on the dose coefficients for ingestion or inhalation [G15].

28. One of the factors regarding the uncertainty of the external dose assessment concerns how and where personal dosimeters should be worn in order to obtain the best estimate of effective dose or equivalent dose, as appropriate. In general, a dosimeter is placed on the front of the body; this is satisfactory provided that the dosimeters have been designed to measure $H_p(10)$. In medical radiology, where lead aprons are used, different approaches have been adopted. In some cases, the assessment of effective doses to workers is carried out by means of a dosimeter worn on the trunk, under the apron. Where doses are likely to be higher, for example in interventional radiology, two dosimeters are sometimes used, one worn under the apron and a second worn outside. The purpose of the second dosimeter is to assess the contribution to the effective dose due to the irradiation of unshielded parts of the body [N9]. Where doses are low and individual monitoring is intended only to give an upper estimate of exposure, single dosimeters might be worn outside the apron.

29. Measurements made on phantoms using X-ray beams of 76 and 104 kVp have shown that, while estimates of the effective dose without the lead apron were within 20% of the expected values, estimates with the dosimeter worn on the waist underneath the lead apron were lower than the expected values [M12]. Such results suggest that accurate estimation of effective dose using personal dosimeters under conditions of partial-body exposure remains problematic and that to be fully accurate would probably require that multiple monitors be used, which is not often done. Differing monitoring practices in medical radiology may therefore affect the validity of the data for comparison purposes. Since the position of the dosimeter in relation to the lead apron is not standardized among countries, a large apparent fluctuation of dose values could result unless algorithms that yield more precise estimates are used to convert the measured quantity to effective dose [N9]. Variations in the design of the lead apron itself and in its thickness may represent additional sources of uncertainty. These uncertainties and how they are addressed by dosimetry services could also have an impact on the comparisons made here. In this annex it is assumed that all these parameters have been properly considered in dose estimation.

30. The conversion coefficients for use in radiological protection against external irradiation are given in ICRP Publication 74 [I56]. Except for radon progeny, values of the committed effective dose per unit intake for inhalation, $e_{j,inh}(50)$, and ingestion, $e_{j,ing}(50)$, are found in ICRP Publication 68 [I50], which takes account of the tissue weighting factors in ICRP Publication 60 [I47] and the new lung model in ICRP Publication 66 [I51]. It is assumed that the data provided to the Committee have been based on these conversion coefficients. A number of difficulties may be encountered in determining occupational exposure. These difficulties may be addressed in various ways, as is evident in the variety of monitoring procedures and dose recording practices adopted in countries throughout the world. While some countries have already adopted the recommendations of ICRP Publication 60 [I47], a significant proportion of countries are still using the dose limits and the quantities of ICRP Publication 26 [I43], especially for the first period analysed in the current annex (1995–1999). This may be a factor in explaining the variation in doses for a given practice among different countries. Quantities for radiation exposure and the methodologies for external and internal dose assessment have been well described in the UNSCEAR 2000 Report [U3], and because the measured quantities and the techniques described in that report remain unchanged, the issue need not be addressed further here.

31. Intakes of radioactive material are normally assessed routinely for workers employed in areas that are designated as controlled (specifically in relation to the control of contamination) or in which there are grounds for expecting significant intakes [I13, I55]. However, there are difficulties in comparing data on doses due to intakes of radionuclides in different countries because of the different approaches used for monitoring and to interpreting the results. Several international intercomparison exercises for internal dose assessment have been organized, of which the largest so far was the Third European Intercomparison Exercise on Internal Dose Assessment, organized in the framework of the EULEP/EURADOS Action Group [D11, I15]. The most important lesson from these intercomparison exercises was that there was a need to develop agreed guidelines for internal dose

evaluation procedures in order to promote the harmonization of assessments between organizations and countries. Significant differences were revealed among laboratories in their approaches, methods and assumptions, and consequently in their results. One major source of divergence at the time of the exercise was due to the particular ICRP models used. Most dosimetry services were using the models from ICRP Publications 26 [I43] and 30 [I44] for legal reasons. However, most were in the process of moving to the new generation of ICRP models (Publications 56 [I46], 60 [I47], 66 [I51], 67 [I49], 68 [I50], 69 [I52], 71 [I53], 72 [I54], 78 [I55] and 100 [I58]), partly because these are considered to be more realistic and partly because of the imminent implementation of the International Basic Safety Standards [I7] and the new Euratom directive, which are based on the new models [C29, D10, D12, H30, I14]. Similar projects aiming to harmonize internal dosimetry procedures have been carried out in different parts of the world under the auspices of the International Atomic Energy Agency (IAEA) [M20].

32. Since its Publication 60 [I47], the ICRP has revised the biokinetic and dosimetric models used in internal dosimetry, specifically: the model for the respiratory tract [I51]; the model for the alimentary tract [I56]; systemic models [I46, I49, I52] and dosimetric models [I54]. The new ICRP biokinetic and dosimetric models have changed the dose coefficients used for internal dosimetry. The ratios of the dose coefficients for workers based on the models of ICRP Publication 68 [I50] to those based on the models of Publication 30 [I44] have been calculated for about 800 radionuclides. For inhalation, about 40% of the ratios fall in the range 0.7–1.5, about 4% of the ratios are greater than 10 and about 1.4% are less than 0.1. For ingestion, about 73% of the ratios fall in the range 0.7–1.5, about 3.4% are greater than 10 and about 1.3% are less than 0.1. The analysis addressed both inhalation and ingestion of radionuclides in the workplace and included almost all the radionuclides (some 800) considered in ICRP Publication 30. The tissues considered were the lungs, stomach wall, colon wall, bone surface, red marrow, liver, thyroid, breast, testes and muscle. The solubility classes were those considered in ICRP Publication 30. Dose coefficients for the absorption types (Types F, M and S) currently used by the ICRP were compared with coefficients for Class D, W and Y compounds, respectively, as defined in ICRP Publication 30. The inhalation dose coefficients generated by the models of ICRP Publication 30 were based on the default particle size of 1 μm (AMAD) recommended in that publication, and the coefficients generated by models of ICRP Publication 68 were based on the default particle size of 5 μm recommended in that publication. As an example, the ratio of the dose coefficient from ICRP Publication 68 to that from ICRP Publication 30 for the inhalation of insoluble ^{239}Pu compound is 0.07 for bone marrow and for the inhalation of insoluble ^{238}U compound is 0.13 for the lung. The ratios clearly depend on the radionuclide and on factors such as retention in the body and solubility [L6, P9].

33. The application of different ICRP methodologies for intake and dose calculations obviously affects the results of dose assessments. This can be an important source of variation between the doses reported by different countries for the period under consideration, when most of the countries changed from ICRP Publication 26 [I43] to ICRP Publication 60 [I47] recommendations.

C. Special quantities for radon

34. The health risk due to exposure to ^{222}Rn (radon) and ^{220}Rn (thoron) comes principally from the inhalation of the short-lived decay products and the resulting alpha particle irradiation of the bronchial airways. The radiation dose delivered to the respiratory system, and the resulting potential health detriment, are a complex function of the radon decay product aerosol characteristics and the physiological parameters of the exposed individual. The radon and thoron dosimetry described in this annex is a summary of section II in annex E of the UNSCEAR 2006 Report [U1].

35. Radon and thoron decay product exposure rates are expressed by the measure of potential alpha energy concentration (PAEC), with units of joules per cubic metre (J/m^3) for the equilibrium equivalent concentration (EEC) or becquerels per cubic metre (Bq/m^3) for the working level (WL: unit of concentration of radon progeny in one cubic metre of air that has the potential alpha energy of 2.08×10^{-5} J for ^{222}Rn). The PAEC is derived from a linear combination of the activities of the short-lived decay products in each radon decay series (see paragraph 122, annex B of the UNSCEAR 2000 Report [U3]). The constants in the linear combination are the fractional contributions of each decay product to the total potential alpha energy from the decay gas. The EEC (in units of Bq/m^3) can be converted to the PAEC by the relationships:

$$1 \text{ Bq/m}^3 = 5.56 \times 10^{-6} \text{ mJ/m}^3 = 0.27 \text{ mWL } (^{222}\text{Rn})$$

and

$$1 \text{ Bq/m}^3 = 7.6 \times 10^{-5} \text{ mJ/m}^3 = 3.64 \text{ mWL } (^{220}\text{Rn}).$$

36. As discussed in annex E of the UNSCEAR 2006 Report [U1], estimates of radiation dose and the resulting risk from inhalation of radon decay products can be derived from either epidemiological studies or dosimetric models. For occupational exposure to inhaled radon decay products, the ICRP recommended in Publication 65 [I48] the use of a single conversion factor based on the results of the uranium miner epidemiological studies, by equating the radiation detriment coefficient (risk per sievert) with the miner detriment (risk per PAEC exposure). For worker exposure, this factor is 1,430 mSv/(J h m^{-3}) (rounded to 1,400 mSv/(J h m^{-3})), 5.06 mSv per working level month (WLM) (rounded to 5 mSv/WLM) or 7.95 nSv/(Bq h m^{-3}) (rounded to 8 nSv/(Bq h m^{-3})) EEC [U1]. The working level month corresponds to the exposure resulting from the inhalation of air containing 1 WL for 170 h. The countries reporting data often do not specify which dosimetric model was used to calculate the dose, although it is likely that the ICRP approach was used [I7].

37. The results of the dosimetric model agree with the conversion convention within a factor of 2 and depend on the value for the radiation weighting factor. Until further clarification of the factor is available, the Committee considers that the established value of 9 nSv/(Bq h m^{-3}) used in past UNSCEAR calculations [U3, U6, U7] is still appropriate for its purpose of evaluating average effective doses [U1].

38. It is not possible to assess the radiation dose due to inhalation of thoron decay products by epidemiological means, and the dose conversion factor must therefore be estimated using dosimetric modelling. Annex A of the UNSCEAR 2000 Report [U3] indicated that a conversion factor for thoron decay products could be derived on the basis of the recommendations given in ICRP Publication 50 [I45], which in turn were based on the results of an Expert Group of the Nuclear Energy Agency [N20]. According to reference [U3], this value is intended to include the dose to organs other than the lungs resulting from the transfer of ^{212}Pb from the lungs to these other organs. The principal dosimetric assessments of lung dose due to deposited thoron decay products support the continued use (see annex E of the UNSCEAR 2006 Report [U1]) of a conversion factor of 40 nSv/(Bq h m^{-3}) EEC.

39. For the present annex, most countries would probably have estimated doses on the basis of ICRP dosimetric factors developed after ICRP Publication 60 [I7, I47]. The ICRP is currently reviewing its biokinetic and dosimetric models, which will certainly influence dose estimation for future evaluations.

II. PUBLIC EXPOSURE

40. Public exposure has been evaluated by the Committee for two broad classes: exposure to natural radiation sources and exposure to man-made sources. In previous reports, these two classes were usually described in separate annexes. In this annex, exposures to these two types of source are considered together. Exposures to man-made sources from peaceful and from military uses of nuclear energy are described separately.

41. The data used in this section have been obtained in the same way as for previous UNSCEAR reports, i.e. from the UNSCEAR Global Survey on Public Radiation Exposures, conducted by means of questionnaires distributed to member States by the UNSCEAR Secretariat, and from the published scientific literature. There are many uncertainties associated with the information provided here, owing to the different ways in which countries collect, analyse and manage their own data. These uncertainties reflect differences in the methodologies for sampling, measuring, treating and reporting the data, as well as differences in assessment approaches, for example the use of different dose conversion factors. The Committee recognizes that there is a need to establish standard methodologies to be used worldwide in order to improve the comparison and manipulation of reported data and therefore to be able to draw more reliable conclusions.

A. Natural sources

42. Human exposure to natural radiation sources has always existed. The earth has always been bombarded by high-energy particles originating in outer space that generate secondary particle showers in the lower atmosphere. Additionally, the earth's crust contains radionuclides. For most individuals, exposure to natural background radiation is the most significant part of their total exposure to radiation. Radon is usually the largest natural source of radiation contributing to the exposure of members of the public, sometimes accounting for half the total exposure from all sources [W6].

1. Cosmic radiation

43. Cosmic radiation can be divided into different types according to its origin, energy and type, and the flux density of the particles. When only the types important for exposure of humans are taken into account, there are three main sources of such cosmic radiation: galactic cosmic radiation, solar cosmic radiation and radiation from the earth's radiation belts (Van Allen belts) [S30].

44. Besides the shielding provided by the earth's magnetic field, which is discussed in section II.A.1(c) below, life is shielded against this radiation by an air layer of approximately 10,000 kg/m^2 (1,000 g/cm^2), which is comparable to a 10 m thick water layer. As a result, at sea level the cosmic radiation contributes about 10% of the total dose rate from natural radiation to which human beings have always been exposed. However, at higher altitudes in the atmosphere or in space, cosmic rays constitute the dominant radiation fields [H20].

45. These cosmic rays interact with the nuclei of atmospheric constituents to produce a cascade of interactions and secondary reaction products that contribute to cosmic ray exposures. These decrease in intensity with increasing depth inside the atmosphere, from aircraft altitudes to ground level. The cosmic ray interactions also produce a number of radioactive nuclei known as cosmogenic radionuclides. The cosmogenic radionuclide most relevant to public exposure is ^{14}C.

(a) Galactic cosmic radiation

46. Galactic cosmic rays (GCRs) arise from sources outside the solar system, from deep space. The GCRs incident on the upper atmosphere consist of a nucleonic component, which in aggregate accounts for 98% of the total, and electrons, which account for the remaining 2%. The nucleonic component is primarily protons (85.5% of the flux) and alpha particles (~12%), with the remainder being heavier nuclei (~1%) up to that of uranium [S30, U3].

47. These primary cosmic particles have an energy spectrum that extends from 10^8 eV to more than 10^{20} eV. Below 10^{15} eV, the shape of the energy spectrum can be represented by a power function of the form $E^{-2.7}$, where E is in electronvolts. Above that point, known as the "knee", the spectrum steepens to a power of –3. The highest energy measured thus far is 3.2×10^{20} eV, which was inferred from ground measurements of the resulting cascade interactions in the atmosphere [U3].

48. It is thought that all but the highest-energy cosmic rays reaching the earth originate within our own galaxy. The sources and acceleration mechanisms that create cosmic rays are uncertain, but one possibility (substantiated by measurements from a spacecraft) is that the particles are energized by shock waves expanding from supernovas. The particles are confined and continually deflected by the galactic magnetic field. Their flux becomes isotropic in direction and is fairly constant in time [U3].

49. Above 10^{15} eV, protons begin to escape galactic confinement. This leaves relatively higher proportions of heavier nuclei in the composition of cosmic rays above this energy level. Protons with energies of greater than 10^{19} eV would not be significantly deflected by the intergalactic magnetic field. The fact that the flux of protons of such high energy is also isotropic and not aligned with the plane of the galactic disc suggests that the protons are probably of extragalactic origin. Only astrophysical theories can suggest the origins of these ultra-high-energy cosmic rays [U3].

50. The GCR fluence rate varies with solar activity, being lower when solar activity is higher. The spectrum of GCRs also changes with solar activity; when solar activity is higher, the maximum of the energy spectrum is shifted to higher energies. GCR particles have to penetrate the earth's magnetic field; because of this, a geomagnetic cut-off exists, which is much more important close to the equator than at the geomagnetic poles. The cut-off is characterized by a "rigidity", R_c. Rigidity is defined as the momentum of the cosmic ray particle divided by its charge. Owing to this influence, the number of particles penetrating the atmosphere is higher close to the earth's poles and their spectrum there is softer. Because of this, the effect of solar activity is relatively more important close to the geomagnetic poles [S30].

(b) Solar cosmic radiation

51. Another component of cosmic rays is generated near the surface of the sun by magnetic disturbances. Solar cosmic radiation (SCR) originates from solar flares when the particles produced are directed towards the earth. These solar particle events are comprised mostly of protons (~99% of the flux), with energies generally below 100 MeV and only rarely above 10 GeV. These particles can produce significant dose rates at high altitudes, but only the most energetic contribute to doses at ground level.

52. Solar particle events, in addition, can disturb the earth's magnetic field in such a way as to change the galactic particle intensity. These events are of short duration, typically a few hours, and are highly variable in their strength. They have a negligible impact on long-term doses to the general population. A long-term forecast of solar flares in terms of either intensity or energy spectrum is not possible. Solar flares are more frequent at periods of maximum solar activity, with the largest at the end of such periods. The geomagnetic field also influences the penetration of SCR to the earth's surface. Because of the lower energies, this influence on SCR is much more important than that on GCRs [S30, U3].

53. The most significant long-term solar effect is the 11-year solar activity cycle, which generates a corresponding cycle in total cosmic radiation intensity. Historical solar cycles are shown in figure I. The periodic variation in solar activity produces a similar variation in the solar wind, which is a highly ionized plasma with an associated magnetic field whose varying strength modulates the intensity of galactic cosmic radiation. At times of maximum solar activity, the field is at its highest and the galactic cosmic radiation intensity is at its lowest. An example of the effect of solar modulation on dose rate at aircraft altitudes is shown in figure II.

(c) Van Allen radiation belts

54. The Van Allen radiation belts are formed through the capture of protons (mainly) and electrons by the earth's magnetic field. The proton energy can reach several hundred megaelectronvolts; the electron energy can reach only a few megaelectronvolts and the electrons' penetration is therefore limited. There are two van Allen radiation belts, an internal one centred at about 3,000 km and an external one centred at about 22,000 km from the earth's surface. The daily equivalent dose to the skin in the internal belt could reach several tens of sieverts for protons and several thousands of sieverts for electrons. The internal radiation belt descends rather close to the earth's surface in the region called the South Atlantic Anomaly, which is centred at about 800 km east of Porto Alegre, Brazil [S30].

(d) Effects of latitude and altitude

55. *Latitude effects.* The earth's magnetic field reduces the intensity of cosmic radiation reaching the upper atmosphere. The shape of the earth's magnetic field is such that only particles of higher energies can penetrate at lower geomagnetic latitudes. This produces the "geomagnetic latitude effect", with intensities and dose rates minimal at the equator and maximal near the geomagnetic poles. The latitude effect at 20 km altitude is shown in figure III.

56. Near the earth, the geomagnetic field acts as a separator of the incident cosmic particles according to their energy (in reality, according to their rigidity). The relationship between particle energy and rigidity, which defines the threshold below which particles are unable to reach a particular location because of the effective shielding by the geomagnetic field [B23], is:

$$E = \sqrt{(RZe / A)^2 + m^2} - m$$

where E is the energy per nucleon in GeV, R is the rigidity in GV, Ze is the nuclear charge, A is the atomic weight and m is the nucleon mass in GeV [O1]. For highly energetic protons, the particle energy and rigidity are quite similar. Each geomagnetic latitude may be characterized by a cut-off rigidity, such that particles with less rigidity cannot arrive at this latitude. The cut-off rigidity (R_c) is given by:

$$R_c = 14.9 \cos^4(\lambda)$$

where λ is the geomagnetic latitude. Equatorial latitudes are the most protected regions. Only particles with rigidities greater than 15 GV and protons with energies of greater than 14 GeV are able to reach the equatorial regions [B14].

57. *Altitude effects.* High-energy particles incident on the atmosphere interact with atoms and molecules in the air and generate a complex set of secondary charged and uncharged particles, including protons, neutrons, pions and lower-Z nuclei. The secondary nucleons in turn generate more nucleons, producing a nucleonic cascade in the atmosphere. Neutrons, because of their longer mean free path, dominate the nucleonic component at lower altitudes. As a result of the various interactions, the neutron energy distribution peaks at between 50 and 500 MeV. A lower energy peak, at around 1 MeV, is produced by nuclear de-excitation (evaporation). Both components are important for the assessment of cosmic ray exposures.

58. Pions generated in nuclear interactions are the main source of other components of the cosmic radiation field in the atmosphere. Neutrally charged pions decay into high-energy photons; these produce high-energy electrons that in turn produce more photons and so on, resulting in the "electromagnetic" or "photon/electron" cascade. Electrons and positrons dominate the charged particle fluence rate at middle altitudes. Charged pions decay into muons, whose long mean free path in the atmosphere makes them the dominant component of the charged particle flux at ground level. They are also accompanied by a small flux of "collision" electrons that are generated along their path.

59. The changing components of dose caused by secondary cosmic ray constituents in the atmosphere are illustrated in figure IV. At ground level, the muon component is the most important contributor to dose, while neutrons, electrons, positrons, photons and protons are the most significant components at aircraft altitudes. At even higher altitudes, the heavy-nuclei component must also be considered.

(e) Exposure to cosmic radiation

60. *Exposures at ground level.* At ground level, muons (with energies mainly of between 1 and 20 GeV) constitute the dominant component of the cosmic ray field. They contribute about 80% of the absorbed dose rate in free air arising from the directly ionizing radiation; the remainder comes from electrons produced by the muons or present in the electromagnetic cascade. In the early literature, these two components of the charged particle flux were referred to as the "hard" and the "soft" component, respectively, with reference to the difference in their penetrating power, the electrons being much more readily absorbed by any shielding. As altitude increases, electrons become more important contributors to the dose rate.

61. The dose rate from the photon and ionizing component is known to vary with latitude, but the variation is small. The dose rate is about 10% lower at the geomagnetic equator than at high latitudes. Considering the population distribution with latitude, an average dose rate in free air at sea level of 31 nGy/h has been adopted by the Committee [U3]. This figure also takes into account the variability due to the solar cycle, estimated to be about 10%. The population distribution of the effective dose rates outdoors at sea level due to the ionizing component of cosmic rays is shown in table 4. The worldwide population considered was 4×10^9 persons [U3]. Because the main contributors to human exposure at ground level are muons, a radiation weighting factor of 1 is assumed, leading to a worldwide average annual effective dose at sea level of about 0.27 mSv.

62. The ionizing component is, however, strongly dependent on altitude. For the same latitude, a variation by a factor of about 4 in the absorbed dose rate in free air was measured in China between sea level and 4,000 m altitude in Tibet [W2]. Dose rates in Switzerland were estimated to be in the range 40–191 nSv/h, with an average value of 64 nSv/h. Combining the results for dose rates with population density, the average per caput dose rate in Switzerland was estimated to be 46 nSv/h [R23]. Estimates of cosmic ray dose rates at elevations above sea level are made using a procedure published by Bouville and Lowder [B45]:

$$\dot{E}_1(z) = \dot{E}_1(0)\left[0.21\, e^{-1.649\, z} + 0.79\, e^{-0.4528\, z}\right]$$

where $\dot{E}_1(0)$ is the dose rate at sea level and z is the altitude in kilometres. Some two thirds of the world population lives in coastal regions, but because dose rates increase with altitude, the dose rates of populations at high altitudes contribute proportionately more to the weighted average. For the directly ionizing and photon component, the population-weighted average dose rate is 1.25 times that at sea level. Using a shielding factor of 0.8 and an indoor occupancy fraction of 0.8, the worldwide average annual effective dose due to the ionizing component of cosmic radiation is estimated to be about 0.28 mSv.

63. For the neutron component, both latitude and altitude strongly affect exposure rates. A latitude-averaged fluence rate at sea level of 130 m^{-2} s^{-1} for latitude 50° N has been derived. The effective dose rate obtained, applying a weighting factor for the neutron fluence energy distribution of 0.02 pSv/m^2, is 9 nSv/h. The shape of the neutron energy spectrum at habitable altitudes is considered to be relatively invariant, and therefore it is expected to be generally valid to use a simple coefficient to convert fluence to effective dose (isotropic). On this basis, the annual effective dose at sea level and at 50° latitude due to neutrons is estimated to be 0.08 mSv.

64. Neutrons arise from collisions of high-energy protons within the upper atmosphere. Incoming protons that initiate the cosmic ray neutron field are strongly affected by the earth's magnetic field, with the effect that the neutron fluence rate in equatorial regions is less than that in polar regions. Florek et al. [F11], quoting results of the Los Alamos LAHET code system calculation, suggest that the equatorial neutron fluence rate at sea level is 20% of the polar fluence rate and that the fluence rate at 50° latitude is 80% of the polar fluence rate. The world population-weighted average effective dose rate at sea level due to cosmic ray neutrons thus determined is 5.5 nSv/h or 0.048 mSv/a [U3]. The population distribution for the effective dose rates outdoors at sea level due to the neutron component of cosmic rays is also shown in table 4.

65. For the neutron component of cosmic rays, there is also a substantial altitude effect. Bouville and Lowder [B45] used both measurements and calculations to derive expressions of the altitude dependence at habitable elevations around the world:

$$\dot{E}_N(z) = \dot{E}_N(0)\, b_N\, e^{a\,z}$$

where $\dot{E}_N(0)$ is the effective dose rate at sea level due to neutrons:

$b_N = 1$ and $a = 1$ km^{-1} for $z < 2$ km;

$b_N = 2$ and $a = 0.7$ km^{-1} for $z > 2$ km [U6].

66. Combining these altitude–dose relationships with their analysis of the distribution of the world population with altitude, these investigators derived estimates for the population-weighted average dose rate due to neutrons as 2.5 times the value at sea level. Using a shielding factor of 0.8 and an indoor occupancy fraction of 0.8, the world average annual effective dose due to the neutron component of cosmic radiation is estimated to be 0.1 mSv. The population-weighted average annual doses for each hemisphere and for the world are summarized in table 5. Overall, the range of average annual effective dose to the world population is 0.3–2 mSv, with a population-weighted average of 0.38 mSv [U3].

67. *Exposures at aircraft altitudes.* Exposure to cosmic radiation increases rapidly with altitude. Persons who fly frequently are exposed to elevated levels of cosmic radiation of galactic and solar origin and to secondary radiation produced in the atmosphere, aircraft structure, etc. The cosmic particle flux depends on solar activity and solar eruptions. The radiation field at aircraft altitudes consists of neutrons, protons, and neutral and charged pions. Neutrons contribute 40–80% of the equivalent dose rate, depending on altitude, latitude and time in the solar cycle.

68. Commercial transport aircraft altitudes are typically 6,100–12,200 m, where the dose rate doubles for every 1,830 m of increased altitude. The aircraft fuselage provides little shielding against cosmic radiation [B43, W5]. Exposures of aircrew are described in section III.B.1 of this annex. The dose received during a particular flight depends on altitude, latitude and flight time. For altitudes of between 9 and 12 km and a latitude of 50° (corresponding to a flight from northern Europe to North America), the dose rate is generally in the range 4–8 μSv/h. Dose rates at lower latitudes are generally lower; hence a dose rate of 4 μSv/h may be used to represent the average dose rate for all long-haul (e.g. trans-Atlantic) flights. For short-haul flights the flight altitude is generally lower, between 7.5 and 10 km. At this altitude, the dose rate is typically 3 μSv/h. These average dose rates include an allowance for the dose received during the climb and descent phases of the flight. A study in the United Kingdom estimated an average per caput dose of about 30 μSv to the United Kingdom population due to radiation exposure during air travel. However, this value cannot be extended to the populations of all countries, because the exposure is strongly influenced by the frequency of air travel, which in turn depends on the country's economic and development level [W6].

(f) Cosmogenic radionuclides

69. The interaction of cosmic radiation with nuclei present in the atmosphere produces elementary particles and also a series of radionuclides. A comprehensive list of cosmogenic radionuclides (with their properties, production rates and average tropospheric concentrations) was included in the UNSCEAR 2000 Report [U3]. Production is greatest in the upper stratosphere, but some energetic cosmic ray neutrons and protons survive into the lower atmosphere, producing cosmogenic radionuclides there as well. Production is dependent not only on altitude but also on latitude, as well as varying with the 11-year solar cycle, which modulates cosmic ray penetration through the earth's magnetic field.

70. Except for ^{3}H, ^{14}C, ^{22}Na and ^{7}Be, which are isotopes of elements with metabolic roles in the human body, the cosmogenic radionuclides contribute little to radiation doses and are of relevance mainly as tracers in the atmosphere and, after deposition, in hydrological systems [U3]. Carbon-14 ($t_{1/2}$ = 5,730 a) arises from the interaction of slow cosmic neutrons with ^{14}N. Transformed into $^{14}CO_2$, it participates in the photosynthetic cycle. Today, the specific activity of ^{14}C is approximately 230 Bq/kg of total carbon, and the content in the human body is about 2,700 Bq, resulting in an average annual individual effective dose of about 12 μSv.

71. The production of ^{14}C from cosmic ray neutrons is relatively constant at an annual rate of 1.4 PBq, resulting in a global atmospheric inventory of 140 PBq [U10]. A best estimate of the specific activity of naturally produced (cosmic ray) ^{14}C prior to industrialization is 222 Bq/kg of total carbon [N7]. The nuclear test explosions from the 1950s and 1960s introduced an estimated 0.35 EBq. This was absorbed into the marine environment with a half-life of about 6 a. The specific activity of ^{14}C from weapons residues is currently about 0.05 Bq/kg in the atmosphere. Releases from nuclear power reactors are also very small. It has been suggested that the addition of $^{12}CO_2$ from the burning of fossil fuels would dilute the naturally produced ^{14}C and that the measurement of the $^{14}C/C$ ratio could then be used as an indicator of the carbon addition to the planet on a global scale [S44]. Ongoing measurements and recent data available are not conclusive in this respect, as current specific activity levels of ^{14}C are still slightly higher than those observed in 1950 [R18].

72. Tritium ($t_{1/2}$ = 12.3 a) results from the interaction of cosmic rays with nitrogen and oxygen nuclei; the tritiated water produced participates in the water cycle. Its concentration level is about 400 Bq/m^3 in continental water and 100 Bq/m^3 in the oceans. On average a human ingests 500 Bq/a, with a resulting average annual dose of 0.01 μSv.

73. Beryllium-7 ($t_{1/2}$ = 53.6 d) has a concentration of 3 mBq/m^3 in air. It reaches the earth in rainwater, thus contributing to an annual commitment for individuals of approximately 1,000 Bq through the ingestion of fresh vegetables, delivering an annual effective dose of 0.03 μSv.

74. The annual commitment of ^{22}Na ($t_{1/2}$ = 949.7 d) is approximately 50 Bq, but this contributes an annual effective dose of approximately 0.15 μSv, significantly more than for tritium. The radiation exposure of populations due to cosmogenic radionuclides is therefore dominated by the production of ^{14}C and is slightly greater than 12 μSv/a [M22].

2. Terrestrial radiation

75. Naturally occurring radionuclides of terrestrial origin, also termed primordial radionuclides, are present in various degrees in all environmental media, including the human body. Only those radionuclides with half-lives comparable to the age of the earth, and their decay products, exist in sufficient quantity to contribute significantly to population exposure. Exposures to radon have been described in annex E of the UNSCEAR 2006 Report [U1].

(a) Sources of external radiation exposure

76. The main contribution to external exposure comes from gamma-emitting radionuclides present in trace amounts in the soil, mainly ^{40}K and the ^{238}U and ^{232}Th families. Information on outdoor exposure comes from direct measurements of dose rate or from evaluations based on measurements of radionuclide concentrations in soil. The 2004 UNSCEAR Global Survey on Public Radiation Exposures, which also sought information on the numbers of people exposed, has provided information on the distribution of doses according to specified ranges and on the average and range of radionuclide concentrations in soil. Data on absorbed dose rates in air for various countries, including data for high- and low-background areas, are given in table 6.

77. Additional information on both external dose rates and radionuclide concentrations in soil is available in the recent literature, as there has been expanded interest in mapping countrywide exposures. Some data already collected and complementary to earlier reports [U3] are presented in table A-1, with average and maximum values for ^{238}U, ^{232}Th and ^{40}K concentrations in soil shown in figures V–VII. The new data do not affect significantly the current worldwide average values of 33 Bq/kg for ^{238}U, 32 Bq/kg for ^{226}Ra and 45 Bq/kg for ^{232}Th. The average value for ^{40}K, 412 Bq/kg, is also close to the previous value (420 Bq/kg). Although the average concentrations of natural radionuclides in soils are low, there is a large variation, with reported levels of up to 1,000 Bq/kg for ^{238}U, 360 Bq/kg for ^{232}Th and 3,200 Bq/kg for ^{40}K. Therefore, for the purposes of global dose assessment, these data need to be linked with corresponding population distributions.

78. The data on worldwide average outdoor dose rates presented in table 6 confirm the previous [U3] average value of 58 nGy/h. The data available to date on the distribution of the population with respect to the outdoor absorbed dose rates in air due to terrestrial gamma radiation are presented in table 7. The mean value for this distribution is in the range 50–59 nGy/h.

79. Indoor exposures depend on radionuclide concentrations in outdoor soil and in building materials. The relative contribution from each source is highly dependent on the type of house and building material. Information on distributions of indoor exposures derived from direct measurements is not extensive, but these can be assessed on the basis of information on soil, shielding and building material, and then linked with the number of people exposed in order to estimate population exposures. Extensive information is being gathered worldwide regarding activity concentrations in building materials. New information, complementing that in reference [U3], is given in table A-2. In general, average

values for natural radionuclides are higher in most building materials than in soils, with granite and marble presenting the highest average values for ^{226}Ra (77 Bq/kg) and with granite also presenting the highest average values for ^{232}Th (84 Bq/kg) and ^{40}K (1,200 Bq/kg).

80. Table 6 also confirms the previous value of 1.4 for the ratio of indoor to outdoor exposure rates. Therefore the value for the worldwide average indoor absorbed dose rate in air of 84 nGy/h given in reference [U3] is considered to be still valid. Using 0.7 Sv/Gy as the conversion coefficient from absorbed dose rate in air to the effective dose received by adults, and 0.8 for the indoor occupancy fraction, the average annual effective dose due to external exposure to natural terrestrial sources of radiation is 0.48 mSv, with 0.41 mSv related to indoor occupancy and 0.07 mSv to outdoor occupancy. The average levels for countries are mostly in the range 0.3–0.6 mSv.

81. Equation (3) is useful for calculating average outdoor gamma ray exposure rates from global soil concentrations in table A-1. These average and standard error soil concentrations are: ^{40}K: 400 ± 24 Bq/kg; ^{238}U: 37 ± 4 Bq/kg; and ^{232}Th: 33 ± 3 Bq/kg. The table 1 DCF_{soil} coefficients are 0.0417, 0.462 and 0.604 nGy/h per Bq/kg, for ^{40}K, ^{238}U and ^{232}Th, respectively, and the calculated outdoor terrestrial gamma ray exposure rate is estimated as 54 nGy/h. Using 0.7 Sv/Gy as the conversion coefficient from absorbed dose rate in air to the effective dose received by adults, and 0.2 for the outdoor occupancy fraction, the average annual effective dose due to external exposure to natural terrestrial sources of radiation is 0.066 mSv, in close agreement with the estimated average based on absorbed dose rate measurements. For indoor environments, the estimated dose rate is then 0.43 nGy/h. This can be taken as the contribution from the soil material, and the difference between this value and the worldwide average value can mainly be attributed to the contribution from building materials to indoor exposure.

82. Figure VIII shows the distribution of population with respect to external dose rates outdoors for 38 countries. From the left-hand figure, it can be seen that the largest population fraction is in the 50–59 nGy/h range, confirming the previous estimates for external dose rate outdoors. From the right-hand figure, it can be seen that about 90% of the world population for which data have been provided for this annex falls within the range of about 20 to over 100 nGy/h. The Committee has decided to revise the range previously adopted for external dose rate (0.3–0.6 mSv/a) to 0.3–1.0 mSv/a.

(b) Internal exposures due to radionuclides other than radon

83. Internal exposures arise from the intake of terrestrial radionuclides by inhalation and ingestion. Doses due to inhalation result from the presence in air of dust particles containing radionuclides of the ^{238}U and ^{232}Th decay chains. The dominant components of exposure due to inhalation are the short-lived decay products of radon, which because of their significance were considered separately in annex E of the UNSCEAR 2006 Report [U1].

84. The inhalation of natural radionuclides other than radon and its decay products makes only a minor contribution to internal exposure. These radionuclides are present in air because of the resuspension of soil particles. The decay products of radon are present because of radon gas in air. Assuming a dust loading of 50 μg/m^3 and ^{238}U and ^{232}Th concentrations in soil of 25–50 Bq/kg, the concentrations in air would be expected to be 1–2 μBq/m^3, and this is generally what is observed. There is, however, a large variability associated with this value, as local levels may be affected by several factors, such as climate, soil class and concentrations in soil. Other factors affecting the variability of natural radionuclide concentrations in air are the contribution to the dust loading of air from burning fuels, because, while organic content is usually deficient in uranium compared with soil, fly ash contains much higher concentrations of uranium. In addition, at coastal locations, concentrations of uranium in air may be an order of magnitude lower than in continental or industrialized areas inland.

85. In the UNSCEAR 1993 Report [U6], representative values of the concentrations of terrestrial radionuclides in air were selected. Because the database has changed very little, most of those values are still considered valid. The highest concentration, 500 μBq/m^3, is for ^{210}Pb. The concentrations of the other radionuclides are: 50 μBq/m^3 for ^{210}Po; 1 μBq/m^3 for ^{238}U, ^{226}Ra, ^{228}Ra and ^{228}Th; 0.5 μBq/m^3 for ^{232}Th and ^{230}Th; and 0.05 μBq/m^3 for ^{235}U. The age-weighted annual effective dose due to the inhalation of radionuclides from the uranium and thorium series in air was estimated to be about 0.006 mSv [U3].

86. Doses from ingestion are mainly due to ^{40}K and to the ^{238}U and ^{232}Th series radionuclides present in foods and drinking water. The ingestion of natural radionuclides depends on the consumption rates of food and water and on the radionuclide concentrations. Reference food consumption profiles were derived in the UNSCEAR 2000 Report [U3] and are summarized in table 8. Although the tabulated values are in reasonable agreement with other assessments, substantial uncertainties are implicit in their mode of derivation. Moreover, there are large deviations from this profile for various parts of the world because of differences in dietary habits (for example, milk consumption in Asia and leafy vegetable consumption in Africa are lower). The values in table 8 are to be seen only as reference values; actual values vary widely.

87. The concentrations of naturally occurring radionuclides in foods vary widely because of differences in the background levels in soil, the climate and the agricultural conditions that prevail. There are also differences in the types of local food included in categories such as vegetables, fruits and fish. It is therefore difficult to select reference values from the wide ranges of concentrations reported.

The relevance of specific nuclides to the dose depends on the soil composition, and the ratio of uranium to thorium varies from place to place, as shown in figure IX, leading to large variations in the activity ratios between their daughters, e.g. the $^{226}Ra/^{228}Ra$ ratio. The soil type also affects the retention/mobility of radionuclides in soil and their availability to plants [F17]. The annual intakes of radionuclides from the uranium and thorium series in various countries have an approximately log-normal distribution for each radionuclide and span an order of magnitude. The highest concentrations are for ^{210}Pb and ^{210}Po, which have similar distributions. The lowest concentrations are for ^{230}Th and ^{232}Th, which also have similar distributions, while ^{226}Ra and ^{238}U have intermediate concentrations [U3].

88. Because drinking water is important for the intake of uranium and radium radionuclides, it is necessary to ascertain that this source of ingestion intake has been included in dietary intake estimates. The radionuclide contents in natural water and tap water have been reviewed; spring and mineral water have also been of particular interest. Some new data are available and are summarized in table A-3. Worldwide there is a huge variability in concentrations of natural radionuclides in drinking water. Figure X shows the ranges cited by countries for uranium. There is a variation of about eight orders of magnitude among individual water samples. The consequence of such variation is a high variability in the values for global per caput doses. Figure XI shows the distribution of average values for ^{238}U given in table A-3, where there is a variation of three orders of magnitude among worldwide average values.

89. Several authors have emphasized the disequilibrium between ^{234}U and ^{238}U in water. A survey of levels in natural bottled water from northern Italy has shown ratios of $^{234}U/^{238}U$ concentrations ranging from 0.99 to 1.63 [R21]. A survey of water from the Euphrates River showed ratios in the range 0.75–3.11. A survey that included measurements of tap and well water in the United States showed ratios in the range 1.16–2.92. At one location, a value of 5.5 was observed; at another location, a ratio of 0.37 was observed for spring water [F9]. Average ratios are of the order of 1.5, which means that doses due to water ingestion for ^{234}U are underestimated if they are based on ^{238}U measurements alone assuming radioactive equilibrium.

90. Uranium is retained in the body primarily in the skeleton. It has been found that the concentrations in various types of bone (vertebrae, rib and femur) are approximately similar but show a large variability among different countries and different age groups [F9]. An earlier estimate was that 70% of the body content of ^{238}U was in the bone. Assuming the reference concentration of ^{238}U in bone to be 100 mBq/kg, this would correspond to 500 mBq in the skeleton and 710 mBq in the whole body. The average concentration in soft tissues would then be 3 mBq/kg, with higher concentrations measured in the lungs and kidneys. Reference values for concentrations in tissues are presented in table 9. The distributions of measured values in bone for radionuclides of the uranium and thorium series are presented in figure XII [U3].

91. Following intake by ingestion and inhalation, thorium is deposited mainly on bone surfaces, where it is retained for long periods. Metabolism models assume that 70% of the body content of thorium is retained in the skeleton. From the reference concentrations given in table 9 and assuming the cortical and trabecular bone masses to be 4 kg and 1 kg, respectively, it may be estimated that the body burdens are 210 mBq of ^{230}Th and 70 mBq of ^{232}Th. The distributions of uranium and thorium concentrations in bone are typically log-normal within a country. The combined values for various countries have an approximately log-normal distribution and extend over an order of magnitude, with the variability being caused primarily by differences in intake of the radionuclides in food and water. The distributions for ^{238}U and ^{230}Th concentrations in bone are similar; somewhat lower concentrations are reported for ^{232}Th. As these data are limited, they remain to be confirmed as truly representative.

92. Radium is retained primarily in bone, and concentrations have been measured in many countries. Lead also accumulates in bone. By contrast, polonium is distributed mainly in soft tissues. Even in the absence of direct intake, both lead and polonium would still be present in the body because of the decay of ^{226}Ra, but direct dietary intake is of the greatest importance in establishing the content in the body. Early measurements showed the $^{210}Pb/^{210}Po$ concentration ratio to be 0.8 in bone, 0.5 in the lungs and generally unity in other soft tissues. Some enhancement of ^{210}Po in the liver and kidneys has also been observed. The presence of ^{210}Pb and ^{210}Po in tobacco greatly increases the intake of these radionuclides by smokers; the measured ^{210}Po concentration in the lung parenchyma of smokers is about three times that of non-smokers.

93. The published measurements of ^{210}Po in human tissue were summarized and the averages reported by Fisenne [F9]. The total concentration in the organs and the annual organ equivalent dose are shown in figure XIII. The various measurements of ^{210}Po in tissue were from Finland, Japan, the Russian Federation, the United Kingdom and the United States. The published measurements in bone were reported from the same countries and additionally from France, Germany, New Zealand and Poland.

94. The annual effective dose due to radionuclides from the uranium and thorium series in tissue at the reference concentrations in the human body was evaluated in the UNSCEAR 2000 Report [U3] as 0.12 mSv. Evaluation of the internal doses due to ingestion of radionuclides from the uranium and thorium series was also reviewed in the UNSCEAR 2000 Report [U3] using the reference values of concentrations in foods and worldwide average consumption rates for infants, children and adults. For adults, the estimated annual dose is 0.120 mSv. These two results are in close agreement. The main contributor to this dose is ^{210}Po.

95. Potassium is more or less uniformly distributed in the body following intake in foods, and its concentration in the body is under homeostatic control. For adults, the body content of potassium is about 0.18%, and for children, about 0.2%. With a natural abundance of 0.0117% for ^{40}K in natural potassium, a specific activity for ^{40}K of 2.6×10^8 Bq/kg and a rounded dose conversion coefficient of 0.003 mSv/a per Bq/kg, the annual equivalent doses in tissues from ^{40}K in the body are 0.165 and 0.185 mSv for adults and children, respectively. The same values are appropriate for the effective doses, given the more or less uniform distribution of potassium within the body.

96. The total annual effective dose due to inhalation and ingestion of terrestrial radionuclides is assessed to be 0.29 mSv, of which 0.17 mSv is due to ^{40}K and 0.12 mSv to the long-lived radionuclides in the uranium and thorium series.

(c) Inhalation of radon

97. Exposure to radon has been described in annex E of the UNSCEAR 2006 Report [U1]. The Committee has decided to keep its previous estimates of 1.15 mSv and 0.1 mSv for the average annual per caput effective doses due to natural sources of radon and thoron, respectively [U3]. This represented approximately one half of the estimated dose due to all natural sources of ionizing radiation. Combining the data presented in table 1 of annex E of the UNSCEAR 2006 Report [U1] with recently updated information available from the European Commission [D14], the distribution of average radon concentration indoors among countries is shown in figure XIV. The average values for individual countries ranged from 9 to 184 Bq/m^3. The currently available data fit a log-normal distribution ($r = 0.98$) with a geometric mean of 45 Bq/m^3 (similar to the previous estimated value of 40 Bq/m^3) with a geometric standard deviation of 2.1.

(d) Areas with elevated radiation levels due to natural sources

98. Several areas of the world are known to have levels of exposure due to natural sources of radiation that are in excess of those considered to be "normal background". There is no specific value of dose rate or of activity concentration in the environment that defines what constitutes an "enhanced natural radiation area" (ENRA). Some references cite criteria such as a dose rate of greater than 300 nGy/h or an indoor ^{222}Rn concentration in air of the order of 150 Bq/m^3. However, these are not adequate reference levels, because situations exist in which those levels are clearly not applicable (for example in areas with high levels of exposure to cosmic radiation; areas where the exposure is due to high levels of ^{226}Ra and/or ^{222}Rn in water, often called "dynamic ENRAs"; or areas where the total dose, including external and internal exposures, is higher than the usual range).

99. Despite the lack of specific criteria, such areas are of interest mainly because they have been used to illustrate high chronic levels of radiation to which human beings are currently exposed and to consider the relevance of such exposures to epidemiological studies on the effects of low-dose and low-dose-rate exposures. Some of these areas are listed in table 10. The origins of the higher exposures and the characteristic levels that define the area as an ENRA are included.

100. The results of this preliminary literature review indicate that public exposure to natural radiation may be of special concern in ENRAs. However, most of the currently available data fail to give the number of persons involved; the information provided on "dose distributions" typically relates only to the exposure fields and not to population. Only three countries—the Czech Republic, the Islamic Republic of Iran and Spain—had responded by April 2006 with information on the population dose distribution; their data for high-background areas are presented in table 11.

3. Summary on exposures to natural radiation sources

101. Although it is recognized that a large effort has been made to map natural radiation sources (mainly radon, the most relevant radionuclide), the available information cannot be correlated with other exposure pathways for which data are not yet presented in such a degree of detail. The countrywide radon maps already available for most European countries [D14] and for Costa Rica [M25, M30] have been provided to UNSCEAR. In addition, distributions of external dose rates are available for some countries, and for the United States, the distributions of uranium, thorium and potassium are available on countrywide maps [U28]. Knowing the cumulative exposure to different sources on a geographical basis could change the current exposure assessment and lead to more precise estimates of the distribution of exposures worldwide. This aspect will be further discussed in the conclusion of section II.E of this annex. The new information available does not currently allow estimates to be made to characterize worldwide average exposures to natural radiation that are significantly more accurate than those provided in previous reports. It was therefore decided to maintain the same numerical values but to slightly extend some ranges (see table 12).

102. The values in table 12 are to be seen as "average" values, but it should be kept in mind that the worldwide exposure to each pathway usually follows a log-normal distribution. Therefore they should be seen only as reference values and not as specific to any particular place. In fact, as some exposure pathways are correlated with each other, the actual distribution may vary significantly among different places.

103. Besides the large variability in environmental concentrations and in population habits throughout the world, the rate at which dose is accumulated may also vary as the

individual ages. A study performed in the United Kingdom found that inhalation doses for infants and children are within 20% of those for an adult, while terrestrial gamma rays give effective doses for infants and children that are larger than those for adults by about 30% and 15%, respectively. The variation of ingestion doses between individuals is comparable to that of doses from terrestrial gamma rays [K8].

104. Regarding public exposure during aircraft flights, although the estimated doses received by passengers during individual flights are low, collective doses may be quite high because of the huge number of flights worldwide. In addition, doses to specific individuals who fly frequently may make an appreciable contribution to their overall exposure to natural sources.

B. Enhanced sources of naturally occurring radioactive material

105. Activities related to the extraction and processing of ores can lead to enhanced levels of naturally occurring radioactive material (NORM) in products, by-products and wastes. An assessment of the situation related to sites with technologically enhanced levels of NORM has been performed in countries of the European Union [V4]. Nine important categories were identified. This annex uses a similar approach and discusses the disposal or use of waste within the category that generates the waste. Eight of the categories are addressed here: uranium mining and milling; metal mining and smelting; phosphate industry; coal mines and power generation from coal; oil and gas drilling; rare earth and titanium oxide industries; zirconium and ceramic industries; and applications using natural radionuclides (typically radium and thorium). The ninth category (disposal of building material, which is recognized to be of little concern) is not considered here.

106. At least for Europe, the first three categories represent the major contaminating industries with respect to the overall amount of waste produced, though radionuclide levels in products and/or waste from the second three categories may be particularly elevated [V4]. Apart from uranium mining and milling, applications using natural radionuclides and, more recently, zirconium industries, activities related to the other categories have generally not been fully evaluated from the perspective of public exposure, though attempts to characterize them according to the radionuclide content of materials have been made in previous UNSCEAR reports [U3, U6].

107. For past industries, the main concern is related to the sites where residues were left before present standards of radiological protection were established. Many of these sites have already been cleaned up, and residual doses and/or radionuclide contents are known. For industries currently in operation, the main focus relates to effluents, releases from waste and the relevant exposed groups of the population. Descriptions of environmental liabilities (such as waste rock piles, waste basins and contaminated areas) can be a valuable starting point for a database that can be used for future assessments of exposure and dose. The features of uranium mining and milling and the related exposures are described below, together with other fuel cycle exposures, in the section on exposures due to nuclear power production, section III.C.1 of this annex.

1. Metal mining and smelting

108. The metals considered include aluminium, copper, iron (and steel), lead, niobium, tin, zinc, gold and others. The NORM activity in feed material for metal smelting is generally low, and the same is true for most slags and other waste. The concentration of radionuclides in intermediary products and wastes, however, will depend on the content initially present in the ore and on the type of process used to extract the metal. In the case of thermal processes, a large part of the radionuclide content will be concentrated in metallic slags, as, for example, in those from the tin industry [V6].

109. The activity levels in the niobium industry may be high, with pyrochlore containing 10,000–80,000 Bq/kg of ^{232}Th [V4]. In one niobium facility in Brazil, activity levels in waste ranged up to 200,000 Bq/kg of ^{228}Ra (in barium sulphate) and 117,000 Bq/kg of ^{232}Th (in the slag). Exposure of the public due to feedstock or the metal products is not expected. The main pathways for public exposure include contamination of groundwater with radium isotopes and external exposure to slag with high thorium content (if this is not disposed of in an acceptable manner) [I22, P11]. Exposures due to inhalation of resuspended material from tin and niobium slag used as landfill have also been cited [V4].

110. In South Africa, the gold deposits from deep underground mines have low-grade uranium associated with them. Since 1952, 170,000 t of U_3O_8 have been recovered as a by-product of gold mining. Some 6 billion tonnes of mining tailings, containing about 500,000 t of uranium and 200 kg of ^{226}Ra, have been deposited. New tailings are being deposited at a rate of 86 million tonnes annually. Elevated ^{226}Ra concentrations, up to 1.7 Bq/L, have been observed in the discharges. Annual doses to nearby populations have been estimated as up to 0.04 mSv due to the ingestion of water and up to 0.086 mSv due to the ingestion of fish. Annual doses due to ingestion of land food products are much lower, ranging up to about 0.002 mSv. Annual doses to the public due to the inhalation of radon and of dust from the tailings piles have been estimated to be about 0.04 and 0.02 mSv, respectively [W18].

2. Phosphate industry

111. Phosphate rock is used extensively, firstly as a source of phosphorous for fertilizers and secondly for making phosphoric acid and gypsum. Ores typically contain about

1,500 Bq/kg of uranium and radium, although some phosphate rocks contain up to 20,000 Bq/kg of U_3O_8 [P7]. In general, phosphate ores of sedimentary origin have higher concentrations of nuclides of the uranium family. The magmatitic minerals, such as those from Kola (Russian Federation) and Phalaborwa (South Africa), present lower concentrations of nuclides of the uranium family and higher concentrations of nuclides from the thorium family, although the total activity is lower than that from sedimentary minerals [V6]. In 90% of cases, the ore is treated with sulphuric acid. The fertilizers become somewhat enriched in uranium (up to 150% relative to the ore), while 80% of the ^{226}Ra, 30% of the ^{232}Th and 5% of the uranium are left in the phosphogypsum.

112. The processing of phosphoric rocks may generate gaseous and particulate emissions that contain ^{238}U and ^{226}Ra; when discharged to the environment, these nuclides lead to radiation exposure of the population. Local dump sites for phosphogypsum are usually not protected from rainfall and become hydraulically connected to surface waters and shallow aquifers [V4]. The use of phosphate fertilizers in agriculture and of gypsum in building materials is a further source of possible exposure of the public [P7]. Elevated radon exposure of the public can further be expected in sites being developed for housing [V4].

113. For somewhat more than half a century, phosphate ores of marine origin containing ^{226}Ra have been processed in Belgium to produce calcium phosphate for use in cattle fodder. The wastewaters are discharged into two small rivers, one of which is the Laak. Enhanced concentrations of ^{226}Ra are observed along the riverbank, mostly confined to a 10 m strip along both sides of the river, including flooding zones. As of 1999, no dwellings had been built on top of these higher-activity areas and no crops for direct human consumption were grown there, so no immediate threat to the population existed [P6].

114. Prior to 1990, France discharged about 3 million tonnes of phosphogypsum into the Baie de la Seine. After 1990, waste was stored on land. In the United Kingdom, the annual discharge of ^{210}Po exceeded 0.5 TBq in the period 1980–1983. In 1993, about 10 million tonnes of phosphogypsum waste were generated within the European Union, with 15% being recycled (for example as building materials), 25% discharged to sea and 60% stored on land [E16]. The import of phosphate ore to European Union countries decreased by about a factor of 2 between 1985 and 1992, reflecting an increasing tendency to import phosphoric acid directly rather than import the ore itself. This reduced the disposal of uranium to sea, bringing about a large decrease in environmental concentrations of ^{210}Po, but in the process transferring the waste disposal problem back to the ore-producing countries such as Morocco [E13].

115. Phosphate rock can be melted in a furnace at high temperature with sand, iron oxide and coal for the production of elemental phosphorus. The residual solids in the furnace contain ferrophosphorus and calcium silicate, also known as slag [I22]. The slag, which contains ^{226}Ra concentrations ranging from 750 to 1,100 Bq/kg, has been used as construction material in the United States, specifically in communities in south-eastern Idaho. Surveys for external exposure were conducted in 1,472 residences. It was estimated that fewer than 12% of the residences in Soda Spring contained slag, while in Pocatello and Fort Hall no houses were found containing the slag. The highest individual dose rate was estimated to be 1.3 mSv/a, and only nine individuals were identified as receiving more than 1 mSv/a above background. A significant fraction of the public roads, however, contained slag: 27% in Pocatello, 23% in Soda Spring and 20% in Fort Hall [A13].

3. Coal mining and power production from coal

116. The average specific activity of both ^{238}U and ^{232}Th in coal is generally around 20 Bq/kg (range 5–300 Bq/kg). Coal mines in Freital, Germany, which have uranium concentrations of 15,000 Bq/kg coal, are an exception [V4]. During the burning of coal, the organic compounds are converted into gases (water vapour and carbon dioxide), while the inorganic elements, which include the significant naturally occurring radionuclides, are concentrated in the ashes [V6]. In general, the radionuclide enhancement factor in ash is about 10. Leaching from fly ash is low, and therefore there are few restrictions on the use of fly ash in landfill and road construction. The use of fly ash for building construction, however, results in radiation exposure from both direct irradiation and radon exhalation. Dumping fly ash may increase the radiation level around the dump site. The most significant exposure pathways are ingestion and inhalation of the isotopes ^{210}Pb and ^{210}Po [V4]. However, recent studies in the United Kingdom confirm earlier indications that the incorporation of pulverized fuel ash into building materials is unlikely to contravene either current national legislation or the European Union directive [H17, H18].

117. The content of natural uranium in coal from Brazil ranges from 30 to 2,000 parts per million. It is estimated that the burning of 2.2×10^6 t of coal per year discharges about 270 t of U_3O_8 equivalent into the environment [P7].

118. About 50 underground coal mines are located in the Upper Silesian Coal Basin, in the southern part of Poland. The total water outflow from these mines is about 800,000 m^3/d. Waters with high radium content (up to 390,000 Bq/m^3) are found mainly in the southern and central parts of the basin where a thick layer of impermeable clay overlies the coal seams. Radium-bearing waters from coal mining are discharged into surface settling ponds and later into rivers. In some cases, radium isotopes are co-precipitated with barium in these ponds or are absorbed on bottom sediments [C7, W19].

119. Slags derived from coal mined in the vicinity of the town of Tatabánya in Hungary have elevated concentrations

of ^{226}Ra (850–2,400 Bq/kg). The slag has been used as filling and insulating material for building houses, blocks of flats, schools and kindergartens, and to fill playgrounds and roads [N13].

4. Oil and gas drilling

120. During the extraction of oil and natural gas, the natural radionuclides from underground formations are brought to the surface. Elevated activities of ^{226}Ra and ^{228}Ra present in NORM are often released by oil and gas industries, particularly in production waters. During the extraction process, radium is co-precipitated along with barium and strontium. A portion of the radium is deposited during the scale formation process and another portion is discharged to the sea with effluents. Mean concentrations in wastewater are 2 and 2.3 Bq/L for ^{226}Ra and ^{228}Ra, respectively. Although these high activities of radium are present in production water for some platforms, water and sediments sampled at a distance of more than 250 m from the production site had normal background levels, showing that water mixing sufficed to reduce concentrations in the environment [J2, V6].

121. The most important radionuclides in scales and other precipitates are the isotopes of radium, with specific activities ranging from 100 to 1,000 Bq/kg. Activity concentrations in sludges are typically a factor of 100 lower. Concentrations of ^{210}Pb and ^{210}Po in sludge and scales can vary between 20 and 1,000 Bq/kg [V4]. The sludges on the Bacia de Campos oil platforms in Brazil have about 105,000 Bq/kg (maximum 340,000) of ^{226}Ra and 78,000 Bq/kg (maximum 286,000) of ^{228}Ra [M14].

122. Activity levels in scales are of the same order as those in uranium mill tailings and other materials that are regulated because of their potential for ^{222}Rn release. The ^{222}Rn emanation fraction for pipe scale, however, is generally lower than that for typical mill tailings [W10]. The disposal of scale from oil extraction industry installations and of sludge containing NORM can be of environmental significance, with contamination of land being the major concern. The average radium concentrations in soils sampled at an oilfield contaminated with NORM in eastern Kentucky, United States, were 32,560 ± 340 Bq/kg [R2].

123. Tank battery sites, which separate water and sediment from the oil produced, have historically been used for the initial processing of crude oil. The sediment remaining in the pit is an oily, viscous material often called “sludge”. This sludge can be radioactive if NORM is associated with the matrix. A radiological survey conducted on six previously remediated tank battery sites revealed average gamma radiation exposure rates ranging from 27 to 100 μGy/h [H19]. In older scales, the concentrations of ^{228}Th will have increased because of ingrowth. Scales and sludges, particularly those from gas fields, may also contain relatively high levels of ^{210}Pb and ^{210}Po [E13].

124. Waterborne pathways may make a noticeable contribution to the radiation exposure of persons resident on farmland contaminated with residual NORM arising from crude oil recovery operations. Persons living in such areas would incur external gamma exposure and exposure from radon inhalation [R2]. The exposure from dissolution of ^{226}Ra is increased in cases where contaminated soil is located near seawater [A9].

5. Rare earth and titanium oxide industries

125. Bastnaesite and monazite are the most important minerals containing rare earth metals. Bastnaesite has an activity concentration of 900–1,200 Bq/kg for radionuclides in the ^{238}U decay series and 700–7,000 Bq/kg for radionuclides in the ^{232}Th decay series. Monazite, on the other hand, has an activity concentration of 10,000–50,000 Bq/kg for radionuclides in the ^{238}U series and 5,000–350,000 Bq/kg for radionuclides in the ^{232}Th series. In Europe, minimal amounts of waste are produced by these industries [I22, V4].

126. The Brazilian experience is somewhat different. As a consequence of monazite processing for the production of rare earth chlorides, carried out from 1949 to 1992, basically three different kinds of waste were produced: *(a)* the light-mineral fraction (activity concentration 170–320 Bq/g) from the monazite physical purification; *(b)* “cake II” (average content 20% thorium hydroxide and 1% uranium hydroxides, approximate activity concentration 1,820 Bq/g) from the monazite alkaline digestion; and *(c)* mesothorium cake ($Ba(Ra)SO_4$) (approximate activity concentration 4,360 Bq/g). It is estimated that about 3×10^4 t of cake II and 1×10^5 t of mesothorium cake were produced annually. These wastes and residues were disposed in shallow ground silos or in rubber drums, or were buried in trenches. Areas that used the light-mineral fraction as landfill later had to be decontaminated [L1].

127. Similar situations occurred in the United States, with waste originating from a Rare Earths Facility that operated from 1932 until 1973 to produce rare earths and radioactive elements such as thorium, radium and uranium using an acid leaching process. Production of these elements generated radioactive mill tailings that contained residual levels of thorium, radium and uranium. Over several decades, the mill tailings were available for use as landfill material by residents and contractors. Winds also may have spread some of the mill tailings to nearby neighbourhoods. Clean-up actions were performed in the mid-1980s for approximately 120 residential properties in the West Chicago area in Illinois, and later for more than 2,170 properties (covering approximately 400 hectares (1 ha = 10,000 m^2) in and around West Chicago [E5].

128. For titanium production, activity concentrations in the ore are about 300–600 Bq/kg for the ^{238}U decay series and 35–600 Bq/kg for the ^{232}Th series. Specific activities of radium sulphate precipitates in pigments or scales may

be as high as 400,000 Bq/kg, and ^{228}Th levels may be higher than 1×10^6 Bq/kg. Exposure pathways include external irradiation and migration of radionuclides from landfill [V4].

129. Scales formed during titanium dioxide pigment production have ^{238}U series activity concentrations ranging from $<10^2$ to 1.65×10^6 Bq/kg and ^{232}Th series activity concentrations ranging from 4×10^3 to 2×10^6 Bq/kg (the maximum value could apply equally to ^{228}Ra or ^{228}Th). However, the pigments themselves are essentially free of radioactivity [I22].

130. The use of the ensuing waste can also lead to public exposure. During the production of titanium dioxide, most naturally occurring radionuclides originally present in the ore are precipitated as metallic hydroxides, except for radium isotopes (the radium chlorides remain partially soluble and are discarded with wastewaters) [V6]. The processing of monazite in France for rare earth extraction, beginning in 1976, led to the input of significant quantities of ^{232}Th and ^{228}Ra to La Rochelle Bay, within authorized annual limits of 37 GBq and 74 GBq, respectively. Improved waste treatment beginning in 1990 reduced the annual discharges to about 0.5 GBq of ^{232}Th and 6 GBq of ^{228}Ra [E13].

6. Zirconium and ceramics industries

131. The average activity concentrations in zircon and zirconia, respectively, are 600 and 300 Bq/kg for ^{232}Th, and 3,000 and 7,000 Bq/kg for ^{238}U. Except for refractory bricks, where ^{238}U activity concentrations of 10 Bq/kg have been reported, the activity concentrations in the products are comparable to those in the feed material. Long-lived radioactive dust constitutes the main source of radiation exposure, which is mainly due to thorium in the dust [V4]. The zirconium industry and the industrial uses of zirconium may be a source of occupational exposure; only the reuse of solid waste could possibly lead to public exposure [V6]. Doses from gamma radiation emitted from large stockpiles of zircon sand are mainly an issue for workers, but in principle, individuals outside a zircon milling plant may also receive exposure via this pathway if they are sufficiently close to the facility. The critical group would be individuals working in the industrial area surrounding the plant, with a maximum conservative annual effective dose estimated to be about 200 μSv. Individuals may also receive exposure from material deposited outside the plant by storm water runoff and from the inhalation of airborne dust emitted from stockpiles and openings in the plant buildings. In studies from several countries, applying conservative approaches, the maximum annual effective dose received by an individual outside the facility was estimated to be less than 1 μSv from discharges to water and 56 μSv from emissions to atmosphere. In nearby population centres, the dose was found to be negligible [I41].

132. The activity concentrations of uranium and thorium series radionuclides in spent foundry sands or waste are likely to be of the order of 1,000 Bq/kg or less because of the dilution of zircon with other constituents. It is expected that an annual effective dose of the order of 100 μSv is the maximum that could be received by a member of the public as a result of the disposal of these materials in landfill facilities. For the manufacture of zirconia by fusion of zirconium minerals, the main exposure pathways to members of the public are discharges of radionuclides in liquid effluent (floor washings) and stack emissions, and the migration of radionuclides from the landfill disposal of furnace dust. Concentrations of ^{210}Pb of up to 200,000 Bq/kg and ^{210}Po of up to 600,000 Bq/kg in furnace dusts have been found. The maximum dose received by a nearby resident from the release of radionuclides in liquid effluents is negligible. The dose received as a result of plume inhalation and exposure to material deposited from stack emissions was estimated as 37 μSv, of which over 35 μSv was due to dust inhalation. The dose received by a future site user after closure of a landfill facility containing 50 t of furnace silica dust (excluding the dose from indoor radon, for which no realistic estimate was made) was 4.5 μSv, of which 3.8 μSv was due to external gamma exposure.

133. For the manufacture of zirconium compounds by chemical dissolution of zirconium minerals, the main potential exposure pathways to members of the public are those associated with the landfill disposal of pipe scales and silica-containing residues. Chemical processing can produce scales and other residues with radium (^{226}Ra + ^{228}Ra) concentrations of up to a few thousand kilobecquerels per kilogram. A future resident living after closure on a landfill site into which 20,000 t of solid residue had been disposed was estimated to receive a dose of 750 μSv/a, mostly from external gamma radiation. For the chlorination of zircon and the production of zirconium metal, the sludge from the zirconium–hafnium separation process, owing to its radium content and large volume, gives rise to radiological issues similar to those associated with radium-rich mine tailings. Consequently, sludge stockpiled in ponds and piles represents a potential source of public exposure through the migration of radionuclides into the surrounding environment, particularly if the sludge is stored long-term rather than being used elsewhere, for example as a soil conditioner. Although there are obvious benefits in using sludge as a soil conditioner rather than storing it indefinitely in piles, there are radiological implications associated with the use of sludge in this manner. If the ^{226}Ra activity concentration in the sludge is of the order of about 1,000 Bq/kg, this corresponds to a radon flux density per unit ^{226}Ra activity concentration similar to that of normal rocks and soil. Sludge deposited on agricultural fields has been found to give rise to a gamma dose rate of 0.1–1 μSv/h at a height of 1 m and to a radon flux density of 0.44 Bq m^{-2} s^{-1}.

134. Products from the zircon industry, such as ceramic tiles and sanitary ware, have activity concentrations far below 1 Bq/g and would not normally be regarded as giving rise to exposures of concern. However, since these products are essentially building materials, some consideration of their radiological impact on members of the public is warranted. The potential exposure pathways are through

external gamma radiation and inhalation of radon released from the product. Several studies in different countries have found doses attributable to the use of glazed tiles in dwellings to be in the range 19–113 μSv above background. White or near-white porcelain tiles have a higher zircon content than glazed tiles and would therefore be expected to give rise to correspondingly higher doses. The use of porcelain tiles containing about 13% zircon in residences may give rise to doses of up to 120 μSv. The zircon content of glazes applied to sanitary ware is similar to that of glazes applied to ceramic tiles, but since the surface area of sanitary ware glaze in a typical home is far smaller, the radiological impact of the zircon used in the glazes applied to sanitary ware is very small compared with that of ceramic tiles. For refractories, the only potentially significant source of public exposure is the burial of spent refractories at a landfill disposal site. Calculations show that the annual effective dose received by a member of the public from the disposal of furnace lining bricks and refractory nozzles in a landfill, including the dose received as a result of future, uncontrolled residential use of the site, is likely to be no more than a few microsieverts. There are no significant public exposure pathways for the use of zircon as a source of zirconia in glass. For the use of fused zirconia in other applications, the disposal of reject material at a landfill facility is not likely to lead to any significant migration of radionuclides into the surrounding environment. The production processes of zircon ceramic tiles, sanitary ware, ceramic pigments and abrasives do not give rise to any significant exposure pathways to members of the public [I41].

7. Applications of radium and thorium

135. Radium has been extracted from uranium-rich ores. High contamination levels were recorded in soil surrounding a luminizing facility in London, with ^{226}Ra levels of between 0.4 and 400,000 Bq/kg, and with levels for "hot spots" of up to 4,000,000 Bq/kg. Similar concentrations were found in the vicinity of a watch factory at Dieppe, France. Exposures to the public are mainly due to external exposure and radon inhalation [V4].

136. An extensive radiological survey identified several contaminated areas in the vicinity of the former Olen radium facility in Belgium. The major contaminated site was the Bankloop brook, whose bed and banks were contaminated over a distance of 1,400 m with radium and chemical waste (heavy metals) to a depth of up to 1 m. The contamination was mainly confined to a narrow strip 5–10 m wide on one or both sides of the brook. About 64% of the total volume of contaminated soil and sediments, which had an associated external dose rate of over 0.15 μSv/h, was in a residential area. At the mouth of the Bankloop, about 3 hectares of farmland (a former area of flooding) were found to be contaminated with radium up to a depth of 1 m (from deep ploughing). The area is used for pasture. The average dose rates are about 0.3 μSv/h, and the maximum value measured was 5.5 μSv/h.

137. Also close to the site is an area that had previously been lower than its surroundings. The difference in level was removed between 1955 and 1960 by depositing residues of cobalt production, the debris of a building formerly used for radium production and a limited amount of radium extraction residues. The area is 9–10 hectares in size and contains mixed radium and chemical waste to a depth of 3 m. No direct public exposure occurred, because a security fence surrounded the area. Material in the dump contained radium with concentrations of up to 34,000,000 Bq/kg. Some nine or ten stretches of road and several isolated points were found to contain contaminated pavement to a depth of about 0.3 m. About 5% of the 11,000 dose rate measurements performed had values of greater than 0.2 μSv/h. One dwelling (with contaminated material under the veranda) had an average radon concentration in air of 720 Bq/m^3 on the veranda and 370 Bq/m^3 in the living room. Radon measurements were performed in 846 dwellings; only six showed average radon concentrations in air that were greater than 150 Bq/m^3 [V5].

138. Thorium is extracted from the same minerals used for rare earth extraction. Specific activities of feed material are in the range 10^3–10^4 Bq/kg. Thorium has been used in a large number of products and processes. Levels in the products (gas mantles, glass and tungsten) are typically higher than those in the original ore by a factor of 100 [V4]. Discarding industrial waste and gas mantles may require particular attention in order to avoid public exposure [V6].

8. Other exposure situations

139. From 1994 to 1999, there were 53 instances where evidence of radioactivity in ferrous scraps was discovered by steel companies in Taiwan, China. These involved 15 orphan radioactive sources, 16 ^{60}Co-contaminated rebars, 20 NORM-contaminated scraps and 2 cases whose cause was unknown. For the NORM, five possible industrial processes may have been involved: oil production and treatment; heavy mineral sand processing and rare earth processing; copper mining and processing; recovery of ammonium chloride by lime absorption in the ammonium–soda process; and uranium enrichment processes and tailings [C9, C10].

140. At least eight heavily used streets (approximately 3–5% of all civic road surfaces in the downtown area of Tayoyuan City, Taiwan, China) were found to exhibit unusual levels of radiation. Crushed rock debris and coarse sands separated from the asphalt pavement were identified as the source. The activity concentrations of ^{232}Th and ^{238}U were found to range up to about 4,000 and 1,000 Bq/kg, respectively. The dose rate on the road surface reached about 1.3 μSv/h, compared with the usual background level of 0.08 μSv/h on Taiwan [C8].

141. In the town of Monte Alegre, Brazil, an urban area was constructed using stones taken from a nearby uranium anomaly as landfill. The urban area has about 20,000 inhabitants,

and ^{222}Rn concentrations in air indoors are in the range 9–310 Bq/m^3, with an average of about 75 Bq/m^3. A small rural settlement of 3,000 people close to the anomaly shows indoor radon concentrations in air in the range 35–462 Bq/m^3, with a mean value of 116 Bq/m^3 [B27, M21].

142. There has been some concern about the exposure due to waste arising from water treatment. All natural waters contain certain concentrations of naturally occurring radionuclides. These may be enriched in the waste (mainly filter sludge), and the handling, transport and disposal of this waste may cause radiation exposure of operating personnel and of the public. A study performed in Europe concluded that, while the exposure of operating personnel due to direct gamma radiation and the exposure of the driver and the public during the transport and unloading of waste are of no concern, there are two exposure pathways that do need to be considered. The first is the exposure of operating personnel to radon. The dose due to inhalation will be highly dependent on both the radon content in the water and the ventilation of rooms [H23]. An analysis of raw water samples in Germany indicated a median value of 5.9 Bq/L of ^{222}Rn, with only about 1% of samples having concentrations of greater than 500 Bq/L of ^{222}Rn. The "activity transfer factors" reported for radon are about 50 Bq/m^3 and 0.1 Bq/m^3 for 1 Bq/L in water for unventilated and ventilated rooms, respectively. The annual doses for a worker working 2,000 hours in a year in such areas, assuming a ^{222}Rn concentration of 500 Bq/L in water, would be 155 mSv and 0.3 mSv for unventilated and ventilated rooms, respectively. The annual doses corresponding to the geometric mean concentration of 5.9 Bq/L of ^{222}Rn in water would be 2 mSv and 0.004 mSv for unventilated and ventilated rooms, respectively. The second pathway that may deserve attention relates to the use of waste sludges as a fertilizer on arable land. Using very conservative approaches, the estimated annual doses range from 0.02 mSv to 2 mSv for adults, depending on the origin of the water generating the sludge, with the dose for infants being about one order of magnitude higher than that for adults [H23].

143. A similar analysis was performed in the United Kingdom. Exposure scenarios relating to the treatment of tap and mineral waters include the transport, the unloading and the use of the sludges on arable land as a fertilizer. For transporting sludges resulting from the treatment of mineral water with high measured radon content, the annual dose to a member of the public was conservatively estimated as 8×10^{-3} μSv. The corresponding value for sludges resulting from tap water treatment is also negligible. The dose resulting from a single unloading event was found not to exceed 10 μSv for any type of sludge and for any exposure group, even using very conservative approaches [H23].

144. Sludges from tap water treatment can be directly used in agriculture, as fertilizers, while sludges from the treatment of mineral water are fed into a sewage plant, where they are diluted with sludges of other origin, reducing the final radionuclide concentration. Land contamination due to the spread of sludge will depend on the radionuclide concentration in the sludge and on the thickness of the sludge layer on the land. The use of the land for agricultural production can give rise to public exposure via the ingestion pathway. Annual doses in the United Kingdom due to the use of sludges from water treatment as fertilizers were estimated to be in the range 0.01–0.3 mSv for sludges from mineral water and 0.02–33 mSv for sludges from tap water treatment [H23].

145. There are also several sites with residues from former installations around the world. Most of these sites are contaminated with radium from former luminizing industries. Some European countries, such as the United Kingdom and Belgium, as well as the United States and Canada, have such contaminated sites. However, these sites have already been identified and most of them have already been remediated, so that the current levels of public exposure are very low.

9. Summary on exposure to enhanced NORM

146. Several types of facility worldwide that are not related to the use of nuclear energy may give rise to exposures of members of the public from enhanced concentrations of naturally occurring radionuclides in industrial products, by-products and wastes. A large effort is under way at both the national and the international level to assess exposure to NORM and to develop strategies to address existing situations that give rise to exposure [E16, I22]. Table 13 presents a summary of the dose estimates for members of the public in the United Kingdom due to the release of NORM from some typical industries [W6]. Besides these, NORM can also expose people as a result of several common practices, such as the agricultural use of sludges from water treatment, or the use of residues as landfill or building material. Although doses to the public are usually low, of the order of a few microsieverts or less, some critical groups could receive doses in the millisievert range, which may deserve attention. The Committee encourages the further development of inventories and methodologies for dose assessment in order to have a more comprehensive view of the issue in the context of public exposure.

C. Use of man-made sources for peaceful purposes

1. Nuclear power production

147. The Committee has routinely collected data on releases of radionuclides due to the operation of nuclear fuel cycle installations. The UNSCEAR 1993 Report [U6] provided an overview of annual releases of radionuclides for each of the basic types of reactor and other fuel cycle installations since the practice of commercial nuclear power generation began. Data for individual mines, mills, reactors and reprocessing plants were provided for the years 1985–1989. In the UNSCEAR 2000 Report [U3], the data for an additional period, 1990–1997, were assessed.

The present annex provides additional operational data for the period 1998–2002 for nuclear power reactors and for the period 1998–2003 for uranium mining.

148. The generation of electrical energy by nuclear means has grown steadily ever since it started in 1956. The relatively rapid expansion that occurred from 1970 to 1985, an average increase in energy generation of over 20% per year, slowed to a pace averaging just over 2% per year from 1990 to 1995. Although there has been an increase in the decommissioning and the shutdown of nuclear reactors, nuclear energy production is still growing, although with lower rates of increase in generated energy: about 0.2% from 1996 to 2000 and about 0.1% from 2000 to 2005. In addition, the number of countries using nuclear power has increased [I27, I28, I31].

149. The nuclear fuel cycle includes: mining and milling of uranium ore and its conversion to nuclear fuel material; fabrication of fuel elements; production of energy in the nuclear reactor; disposal of irradiated fuel or its reprocessing, with recycling of the fissile and useful materials recovered; and storage, release, treatment and disposal of radioactive waste. For some types of reactor, enrichment of the isotopic content of ^{235}U in the fuel material is an additional step in the fuel cycle. The nuclear fuel cycle also includes the transport of radioactive material between the various installations.

150. Radiation exposures of members of the public resulting from discharges of radioactive material from installations of the nuclear fuel cycle were assessed in previous UNSCEAR reports [U3, U6, U7]. In this annex, the trends in normalized releases and the resultant doses due to nuclear power reactor operation are presented for the years 1998–2002. Doses are estimated using the environmental and dosimetric models described in annex A, "Dose assessment methodologies", of the UNSCEAR 2000 Report [U3].

151. The doses to exposed individuals vary widely from one installation to another, between different locations, with different population habits and with time. Generally the individual doses decrease markedly with distance from a specific source. To evaluate the total impact of radionuclides released at each stage of the nuclear fuel cycle, the results are evaluated in terms of collective effective dose per unit electrical energy generated, expressed as man Sv/(GW a). Only exposures to members of the public are considered in this section. Occupational exposures associated with nuclear power production are addressed in section III of this annex, "Occupational radiation exposure".

(a) Uranium mining and milling

152. In the period 1998–2003, a total of about 35,000 t of uranium was produced annually in 24 countries (table 14). The major producer in this period was Canada, with about 30% of world production, followed by Australia, with 21% of total production. Since the beginning of the nuclear era, 37 countries have been involved in uranium production. The cumulative production up to 2003 is presented in figure XV. Canada produced about 21%, the United States 20% and Germany 12% of the total amount of uranium produced globally up to 2003, except for the amount produced in the former Soviet Union (about 20% of total production) and the production in China before 1990 [O16, O17, O21]. Annual production has decreased since 1990 but since 2000 has been quite stable (figure XVI).

153. There are a large number of mining areas being decommissioned. The countries that have declared mining areas decommissioned or under decommissioning through their National Reports to the Joint Convention on Spent Fuel and Radioactive Waste Management [I38] are Argentina [R13], Australia [C26], Bulgaria [R9], Canada [M28], the Czech Republic [C31], Denmark [N5], France [F14], Germany [F2], Slovenia [R12], Spain [S29] and the United States [U24]. Other countries with environmental liabilities resulting from uranium mining are Brazil [F5], Estonia [R3], Kazakhstan [K12], Romania [B18] and Ukraine [R19].

154. Milling operations involve the processing of the ore to extract the uranium in a partially refined form, known as yellowcake. In 2003, there were 294 uranium milling installations in operation and eight under construction worldwide; 149 installations had already been decommissioned and 231 were shut down or being decommissioned [I28].

155. *Effluents and solid waste.* Mining operations have been carried out in open pits, in underground mines and by in situ leaching. Uranium mill tailings are generated at about one tonne per tonne of ore extracted, and they generally retain 5–10% of the uranium and 85% of the total activity. Typical activity concentrations in the tailings of ^{238}U are 40,000–100,000 Bq/kg and of ^{226}Ra are 1,000–20,000 Bq/kg [V4]. The estimated amounts of tailings worldwide are shown in figure XVII; they total about 2.35×10^9 t. Besides the tailings, waste rock piles may also become a source of public exposure. For open-pit mining, the amount of debris produced is from 3 to 30 tonnes per tonne of extracted ore. For underground mining, about ten times less debris is produced. On the basis of information provided for 13 mining sites in Argentina [R13], Canada [M28], Germany [F2] and Spain [S29], the amount of waste rock varies from 40 to 6,000 times the amount of tailings, with an average value of about 1,600 tonnes of waste rock per tonne of tailings [I38].

156. Tailings are often confined because of the associated risk. At some locations, exposure to radon may be of considerable concern, but it is sometimes not addressed. For example, at some tailings locations, exposure to radon may become important where the site is subsequently used for housing, as has happened in eastern Germany, the Czech Republic and other eastern European countries [V4]. Problems may also arise from exposure via aquatic pathways, since acid drainage can leach uranium from waste piles [A14, F5]. The erosion of covers, structural failure of embankments, seepage to ground or surface water and

emanation of radon are some of the more important mechanisms for release of pollutants to the environment.

157. Critical exposure pathways tend to be site-dependent. The radionuclides of greatest concern for atmospheric pathways are ^{222}Rn, its decay progeny, and airborne particulates containing thorium, radium and lead. The main concern for aquatic pathways is ^{226}Ra, although ^{238}U, ^{230}Th and ^{210}Pb may be equally important [V4]. Many abandoned sites exist, and only a few have been remediated. Problems associated with public exposure resulting from past practices include radon release, water contamination, the proximity of contamination to human settlements, the removal of wastes for construction, large inventories and appreciable aerial dispersion [V4].

158. Some remediated sites related to former uranium mines have follow-up monitoring and assessment programmes on contamination in the environment. Although some limited descriptions of these are available in the literature, little or no useful information exists on exposures to actual population groups, because most assessments were performed conservatively to demonstrate compliance with regulations limiting doses to hypothetical critical groups.

159. There are few new data on releases of radionuclides due to mining and milling operations. Previous UNSCEAR reports have estimated the average release of radon for underground mines as approximately 75 TBq/(GW a). There were no estimates of releases due to open-pit operations. In the UNSCEAR 1993 Report [U6], the average normalized radon release from mills in Australia and Canada was estimated from the limited data available to be 3 TBq/(GW a) [U6]. These values are not expected to change with current mining and milling practices. The long-lived precursors of ^{222}Rn, namely ^{226}Ra (half-life 1,600 a) and ^{230}Th (half-life 80,000 a) are present in mill tailings and constitute a long-term source of radon release to the atmosphere. On the basis of the UNSCEAR 2000 Report [U3], the normalized radon releases are 3 and 1 TBq/(GW a) for operational and abandoned tailings, respectively, and these values are used here. The in situ leach facilities have no surface tailings and little radon emission after closure.

160. *Dose estimates.* The methodology used by the Committee to estimate the collective dose due to mining and milling is described in the UNSCEAR 1977 and 1982 Reports [U9, U10]. Dose estimates are based on representative release rates from a "model" mine and mill site having the typical features of existing sites. The results are therefore not applicable to any particular site without due consideration of site-specific data, and rather are meant to reflect the overall impact of mining and milling facilities. The collective effective dose per unit electrical energy generated is estimated to be 0.2 man Sv/(GW a) during operation of the mine and mill, and 0.0075 man Sv/(GW a) per year of release from the piles of residual tailings of operational mining and milling sites.

161. With the current production of about 35,000 t/a and with the assumption that 12 countries produce more than 500 t/a, the average annual individual effective dose of 25 μSv (which assumes that the collective dose is received by the population within 100 km of the mine and mill sites) is still valid for the major producing countries. Considerable deviations from the representative values of parameters selected are possible for the more general conditions of present practice. There are locations in Brazil, for example, where acid leaching may be responsible for high concentrations in drainage waters from the mining area [A14, F5]. Also, very high population densities are reported in areas surrounding the mills in China. In some cases, previously abandoned tailings may not have been so carefully secured as they might have been. Although careful management of tailings areas would be expected in the future, the extremes in management approaches (from leaving the tailings uncovered to providing secure and covered impoundment) could increase or decrease the estimated exposure by at least an order of magnitude.

(b) Uranium enrichment and fuel fabrication

162. For light-water-moderated and -cooled reactors (LWRs) and for advanced gas-cooled, graphite-moderated reactors (AGRs), the uranium processed at the mills needs to be enriched in the fissile isotope ^{235}U. Enrichments of 2–5% are required. Before enrichment, the uranium oxide (U_3O_8) must be converted to uranium tetrafluoride (UF_4) and then to uranium hexafluoride (UF_6). Enrichment is not needed for gas-cooled, graphite-moderated reactors (GCRs) or heavy-water-cooled and -moderated reactors (HWRs).

163. There were 29 uranium conversion/recovery facilities in operation and 1 under construction in the world in 2003; 2 had already been decommissioned, and 14 had been shut down or were being decommissioned. For uranium enrichment, there were 21 operating facilities, 2 under construction, 5 decommissioned and 7 shut down or being decommissioned. For fuel fabrication or heavy-water production, there were 66 operating facilities, 5 under construction, 23 decommissioned and 27 shut down or being decommissioned [I28]. Nominal capacities for uranium enrichment, hexafluoride conversion and fuel fabrication by country are presented in table 15, while countries with nuclear fuel production facilities are shown in figure XVIII [I35].

164. The releases of radioactive material from conversion, enrichment and fuel fabrication plants are generally small and consist mainly of uranium series isotopes. For the "model" installations, the normalized collective effective dose due to these operations was estimated to be 0.003 man Sv/(GW a). Inhalation is the most important exposure pathway. The collective doses to local and regional groups resulting from liquid discharges comprise less than 10% of the total exposure. The average annual collective dose for the period 1998–2002 is estimated to be 0.8 man Sv. Considering that 18 countries have nuclear fuel enrichment and/or fabrication facilities, the estimated annual individual

effective doses would be about 0.2 μSv for local population groups and about 0.1 nSv for regional groups.

(c) Nuclear power reactors

165. Reactors used for electrical energy generation are for the most part classified according to their coolant systems and moderators: light-water-moderated and -cooled pressurized- or boiling-water reactors (PWRs, WWERs, and BWRs,); heavy-water-cooled and -moderated reactors (HWRs); gas-cooled, graphite-moderated reactors (GCRs); and light-water-cooled, graphite-moderated reactors (LWGRs). These are all "thermal" reactors, in which the moderator material is used to slow down the fast fission neutrons to thermal energies. In fast-breeder reactors (FBRs), there is no moderator, and fission is induced by fast neutrons; the coolant is a liquid metal. FBRs make only a minor contribution to energy production. A list of reactors that operated in the period 1998–2002 and their installed capacities is presented in table A-4, and the worldwide distribution of operational reactors for the same period is shown in figure XIX. The electrical energy generated by these various types of reactor up to 1997 has been presented in previous UNSCEAR reports, and values for individual reactor sites for the period 1998–2002 are given in table A-5 [I31]. A summary for each reactor type is presented in table 16.

166. The average energy generated by nuclear power from 1998 to 2002 was 278 GW(e)/a (net gigawatts of electrical power per year), ranging from 264 GW(e) in 1998 to 288 GW(e) in 2001. The tendency for increasing amounts of energy to be generated by nuclear power continues. The net installed electrical energy capacity of nuclear power plants, the number of operating reactors and the average net installed capacity per unit power reactor are still increasing worldwide (figure XX). In the period 1998–2002 covered by this annex, there were 452 operational reactors. Of these, 23 had started operating in the period, 14 were shut down and 8 had not generated energy in the period. Between 2003 and 2005, 10 new reactors started operation and 8 were shut down. In the same period, there were also 22 nuclear power reactors being built in 10 countries. By 2007, the number being built increased to 30 reactors in 13 countries [I31]. The time trend for total energy generated by reactor type is shown in figure XXI.

167. PWRs contribute the largest fraction of the total nuclear energy generated worldwide, about 67% for the period 1998–2002, followed by BWRs, with a contribution of about 24%. The contributions of other reactor type are: about 5% for HWRs, 3% for LWGRs and 2% for GCRs. FBRs contribute very little, only about 0.1% of the total energy generated. The average contribution for each reactor type can be seen in figure XXII for the period 1998–2002 covered by this annex and for the period 1970–1997. The current smaller contribution from GCRs reflects the interruption in nuclear power production (later resumed) by some reactors in the United Kingdom.

168. The Committee derived average releases of radionuclides from reactors on the basis of reported data; these averages have been used to estimate the resulting exposures for a reference reactor. The geographical location of the reactor, the release points, the distribution of the population, food production and consumption habits, and the environmental pathways of radionuclides are factors that influence the calculated dose. The same release of activity and radionuclide composition from different reactors can give rise to different radiation doses to the public. Thus the calculated exposures for a reference reactor provide only a generalized measure of reactor operating experience but nevertheless serve as standardized measures for analysing longer-term trends from the practice.

169. *Effluents.* Information on effluents released from operating nuclear power plants have been provided by United Nations Member States for the UNSCEAR Global Survey on Public Radiation Exposures, and by the International Atomic Energy Agency (from its DIRATA database [I30]). Data have been published by the European Commission [E15, V2] and the United States [N16, N17, N18, N19]. For the Republic of Korea, data were obtained from the national report to the Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management [I38, R11]. Most of the available data are related to PWRs (including WWERs), BWRs and HWRs, with only very limited information for AGRs GCRs, LWGRs and FBRs. The radioactive material released in airborne and liquid effluents from reactors during routine operation for the period 1998–2002 are reported in tables A-6 to A-12. For airborne effluents, the releases of noble gases (table A-6), tritium (table A-7), ^{131}I (table A-8), ^{14}C (table A-9) and particulates (table A-10) are given. For liquid effluents, the releases of tritium are given in table A-11 and of other radionuclides in table A-12.

170. The normalized releases have traditionally been compiled separately for each reactor type. This is justified because of the different composition of the releases, mainly for noble gases, and different "dose factors" are required to estimate the doses for different reactor types. With relatively complete data, little extrapolation is needed for estimating the collective doses resulting from the total releases, and the normalized values are retained by reactor type mainly for convenience. The results are presented in table 17. These values are intended only for use in estimating the contribution of operating nuclear power plants to the overall public exposure and should not be used for comparison between different reactor types for other purposes. The choice of a specific type of reactor for generating purposes must take into account several aspects, such as the safety of the reactors; the impact of the complete fuel cycle, including waste generation; and the industrial infrastructure available in each country—factors that are not covered in this annex. In addition, effluent releases are dependent on the reactors' age (the performance of older reactors is usually different from that of more modern reactors) and also on improvements in waste management systems. Also, reactors that have had long

shutdown periods for maintenance operations may present higher than usual values because, while effluent discharges may be enhanced, the power generated is zero. The information used in this annex includes the total energy generated and the total effluents released in each year, and these figures do not explicitly take account of the difference due to maintenance periods. Only those reactors that have not generated energy during a whole year have been excluded from this analysis. On the whole, the values for the average release per unit energy generated are consistent with results from previous UNSCEAR reports. In general, normalized releases are decreasing with time.

171. The largest contributions to the activity of the effluents released are associated with tritium and noble gases. From the information available, the release of noble gases per unit energy generated is higher for LWGRs than for other reactor types. The amount of tritium release in both atmospheric and liquid releases is higher for heavy-water reactors. Normalized values for noble gases released from nuclear power plants over different time periods are shown in figure XXIII. Except for LWGRs, all other reactor types show a decrease in the noble gas activity released per unit energy generated; this may reflect improvements in waste management procedures and in the design characteristics of modern reactors.

172. *Local and regional dose estimates.* The concentrations in the environment of released radionuclides are generally too low to be measurable except close to the nuclear facility and then only for a limited number of radionuclides. Therefore dose estimates are based on effluent data. Environmental transfer and dosimetric models were reviewed in annex A, "Dose assessment methodologies", of the UNSCEAR 2000 Report [U3]. Again, because of the variability in annual releases, normalized releases, in TBq/(GW a), are averaged over a five-year period to estimate collective doses. The dose conversion factors used in estimating doses were the same as those used in the UNSCEAR 2000 Report [U3] and were summarized in table 2.

173. The collective doses estimated for local and regional population groups combined are presented in table 18. The collective dose for 1998–2002 is lower than that for the period 1990–1994 given in the UNSCEAR 2000 Report [U3]. The main reasons for this are the lower values for noble gas releases from BWRs and the absence of a contribution from GCRs in the United Kingdom that were not in operation in the period 1998–2002. The average annual collective dose to local and regional groups due to effluents released from nuclear power plants in the period 1998–2002 was estimated as about 75 man Sv. (If the estimates were to be made using a simpler approach, i.e. considering the total effluent releases from all reactors of a specific type divided by the total power generated by those reactors, the averages would be less sensitive to the performance of individual reactors and would probably be a more representative estimate of the worldwide average dose. The results of such a calculation would provide a value for the annual collective dose of about 42.6 man Sv.)

174. To estimate values for the per caput local and regional doses, it is assumed that the total collective dose relates to model population groups around all nuclear power plants: the local population is assumed to lie within a 50 km radius surrounding a nuclear power plant and its population density is taken to be 400 km^{-2}; the regional population is assumed to lie within a 2,000 km radius from the nuclear power plant and its population density is taken to be 20 km^{-2}. Using the model site described in reference [U3], with 444 operational reactor units and an average of two reactors per site, the Committee has estimated that the per caput effective dose due to each site would be about 0.1 μSv annually for local groups (50 km radius) and only a fraction of a nanosievert for the regional groups within a 2,000 km radius surrounding a site.

175. The annual doses estimated for critical groups used for licensing and effluent control of nuclear power plants are considered to apply to the area within a 3 km radius of the reactors and in most countries are constrained by an annual dose limit in the range 200–300 μSv, but actual doses are usually much lower than this. Considering that more than 80% of the collective dose is due to airborne effluents, and taking the difference between the values for dilution factors for the representative source and long-term average conditions as defined in annex A of the UNSCEAR 2000 Report [U3] for the distance of 1 km for the critical group, it can be assumed that, for the period 1998–2002, the expected maximum annual effective doses to critical groups within 1 km of reactor sites due to effluent releases from nuclear power plant operation are of the order of 0.02 mSv.

176. Some information was also available for releases from some shut down reactors. These releases cannot be treated as "operational" releases, because they are not associated with the generation of nuclear energy. The values of the total releases from some shut down reactors are presented in table 19. A comparison of total releases from these reactors with those from operational reactors of a similar type and power shows that releases from shut down reactors are significantly smaller than those from the equivalent operational reactors, although some exceptions may be found, mainly related to old and low-powered shut down reactors.

(d) Fuel reprocessing

177. The reprocessing of spent fuel is performed to separate out and recover reusable uranium and plutonium from waste. Most spent fuel from reactors is retained on site in interim storage, pending decisions on ultimate disposal or retrievable storage. It is estimated that about one third of the spent fuel already produced has been submitted to the reprocessing stage of the nuclear fuel cycle [I34]. France, Japan and the United Kingdom are the main countries operating commercial reprocessing plants.

178. *Effluents.* Relatively large quantities of radioactive material are involved at the fuel reprocessing stage, and the

potential for its release in waste discharges is greater than for other stages of the fuel cycle. Routine releases have been largely in releases of liquid effluents to the sea. Operating standards have been considerably improved at reprocessing plants over the years, with substantial reductions in the amounts released.

179. In 2003, there were 13 fuel reprocessing plants in operation, 3 under construction, 13 decommissioned and 18 shut down or being decommissioned [I28]. Information on releases from some of these installations for the period 1998–2002 is presented in table A-13 for airborne effluents and in table A-14 for liquid effluents. The origins of these data were countries' responses to the UNSCEAR Global Survey on Public Radiation Exposures, the IAEA DIRATA database [I30] and the open literature [E15, V2]. Included are data for the reprocessing facilities at La Hague (France), Karlsruhe (Germany), Krasnoyarsk and Tomsk-7 (Russian Federation), Dounreay and Sellafield (United Kingdom) and Tokai (Japan).

180. Collective doses from nuclear fuel reprocessing can be estimated from the normalized releases per unit energy generated, the electrical energy equivalent of the fuel reprocessed and the collective dose per unit release of radionuclides [U6]. Previous UNSCEAR reports used dose factors based on the electrical energy equivalent of the fuel reprocessed. The same methodology cannot be used here, because information on the amount of fuel reprocessed is not available. Doses were thus estimated on the basis of the activity released in the effluents, using the dose conversion factors presented in table 3. The data collected are currently not complete, and this necessarily introduces large uncertainties into the resulting estimates. Using only the available reported data, the average annual collective dose is estimated as 30 man Sv, with about 8 man Sv due to airborne effluents and about 22 man Sv due to liquid effluents, as shown in table 20. The estimate for the total collective dose since the beginning of reprocessing is 4,828 man Sv. The largest contribution to the total dose estimate is still associated with the release of ^{14}C. The actual values for the total doses, however, are probably a little larger than these estimates, because some data are missing that would be needed to estimate doses accurately.

181. The estimate of the annual collective dose is still in the range 20–30 man Sv; if this were exposing a single local population group (say, 3.1×10^6 persons within a 50 km radius), the per caput effective dose would be about 10 μSv per year of operation. The corresponding value for regional groups would be about 0.12 μSv/a. Considering that five installations have contributed to this collective dose, the average effective doses would be of the order of 2 μSv for local population groups and 0.024 μSv for regional groups.

(e) Globally dispersed radionuclides

182. Radionuclides that are long-lived and easily dispersed in the environment can give rise to doses to people across the whole planet. The radionuclides of specific interest are ^{3}H, ^{14}C, ^{85}Kr and ^{129}I, with half-lives of 12.26, 5,730, 10.7 and 1.6×10^7 years, respectively. The large uncertainties involved in estimating doses over prolonged time periods are due to problems in predicting environmental pathways, population distributions, dietary habits, climate change, etc. The uncertainties in dose calculations increase when the integration is carried out for very long periods of time—hundreds or thousands of years or even longer. Considering the 100-year truncated dose coefficients of 0.004 man Sv/(GW a) for ^{3}H, 6.3 man Sv/(GW a) for ^{14}C, 0.12 man Sv/(GW a) for ^{85}Kr and 0.0008 man Sv/(GW a) for ^{129}I releases [U7], and a continuing practice of about 300 GW a energy production per year, the worldwide maximum per caput effective dose rate would be about 0.18 μSv/a.

(f) Solid waste disposal

183. Solid wastes arise at various stages in the nuclear fuel cycle. They include low- and intermediate-level wastes, mainly from reactor operation; high-level waste from fuel reprocessing; and spent fuel for direct disposal. Low- and intermediate-level wastes are generally disposed of by shallow burial in trenches or concrete-lined structures, but more advanced disposal sites also exist. High-level waste and spent fuel are currently retained in interim storage tanks pending the development of adequate methods for disposal and the selection of disposal sites.

184. The radiological impact assessment of a high-level waste repository has to rely on modelling of the long-term behaviour of the waste and the migration of released radionuclides both near the site and at greater distances over a long period of time. To carry out such performance assessments, a number of site-specific data are needed, including those called for by waste characterization and transport models. Such assessments have been performed, mainly for use in formulating design criteria for the hypothetical repositories.

185. Information on spent fuel has been obtained from the National Reports of countries that are parties to the Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management [I38]. The direct comparison among different countries is difficult because inventories are specified in different ways: some declare the total mass stored, while others declare the uranium mass or the heavy-metal (HM) mass. Other countries report the volume, and a few present the activity (but sometimes it is not clear if the value given refers to the uranium component or if it includes activity from fission products). From the material provided by a few countries that have declared their total inventory of spent fuel by nuclear power plant and also declare that they do not reprocess their spent fuel, average values for the annual spent fuel generation per unit installed electrical capacity have been estimated and are presented in table 21.

186. Considering the number of operating years, the type of reactor and the net electrical capacity, a total amount of about 210,000 t of HM in spent fuel is estimated to have been generated worldwide up to the end of 2002 from nuclear power plants that were operational in the period 1998–2002. This amount includes the material that has already been reprocessed, which amounts to about 90,000 t worldwide [I34]. Because this figure also includes material reprocessed from reactors already shut down, there are at least some 120,000 t of HM in spent fuel from nuclear power plants being stored, most of it currently in temporary storage conditions.

187. Before final disposal, all such material will have to be manipulated and transported, which will give rise to both occupational and public exposures. Public exposure due to the transport of spent fuel is discussed in section II.C.2 of this annex. The transport of radioactive material of various types between nuclear fuel cycle installations may cause members of the public who happen to be near the transport vehicles to be exposed. The transport of radioactive and nuclear material is addressed as a separate item in this annex. For the nuclear fuel cycle, doses may be estimated using the factor of 0.1 man Sv/(GW a), as in previous UNSCEAR reports [U3, U9, U10].

188. The routine operation of nuclear power plants generates large amounts of long-lived and high-activity radioactive waste. Although there is information on waste inventories for several countries, only a few of these inventories are described in detail with respect to the specific origin of the waste. Some countries report the volume after treatment and conditioning while others report the weight produced; care is needed in interpretation. Nevertheless, on the basis of information provided by Argentina [R13], Canada [M28], Hungary [R10], the Republic of Korea [R11], Spain [S29] and Switzerland [D6] in their National Reports to the Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management [I38], the annual amount of radioactive waste generated by different types of reactor per unit installed capacity was estimated, and these results are also presented in table 21.

189. Doses due to solid waste disposal have been estimated on the basis of the projected eventual migration of radionuclides through the burial site into groundwater. These estimates depend critically on the assumptions about the containment of the solid waste and the site characteristics, and accordingly are generally highly uncertain. The approximate normalized collective effective dose due to low- and intermediate-level waste disposal is, however, relatively low, of the order of 0.5 man Sv/(GW a), and is due almost entirely to ^{14}C [U6, U9]. The worldwide average annual per caput effective dose rate would be about 1 nSv per year of practice.

190. The decommissioning of nuclear facilities gives rise to radioactive waste, and decommissioning experience is being accumulated. Worldwide a considerable number of installations have been shut down or are being decommissioned. The 2003 list includes 231 uranium milling facilities, 14 uranium conversion/recovery plants, 7 enrichment facilities, 27 fuel fabrication/heavy-water production facilities and 18 fuel reprocessing plants. Also, 107 commercial nuclear power plants had been shut down or were undergoing decommissioning. There were also 21 research reactors and several research units undergoing decommissioning.

191. According to the information provided by countries in 2005 under the arrangements for the Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management, the largest decommissioning programme in 2005 was that of the United States, which was decommissioning 16 nuclear power reactors, 20 research reactors, 66 radioactive installations and about 1,186 sites formerly used for activities related to defence [U24]. France was decommissioning 9 nuclear power reactors, 15 research reactors, 3 small reactors used for defence activities and 16 other installations [F14]. Germany had 17 nuclear power reactors and 14 research reactors undergoing decommissioning [F2]. All these processes will generate large amounts of radioactive waste, including spent fuel from both research and power reactors, which will have to be handled, transported and disposed of. With the information available it is not possible to estimate the total amount and activity of the waste to be disposed of. The amount of waste will be highly dependent on the facility type, size and operational history. As an example, the Republic of Korea has estimated that some 620 m^3 of waste with an activity of about 1.24×10^{12} Bq will be generated by the decommissioning of two research reactors, and some 380 m^3 of waste with an activity of about 6.5×10^5 Bq by the decommissioning of one conversion facility. The decommissioning of two nuclear power reactors in Canada, at Douglas Point and at Gentilly-1, has left a total of 300 and 80 t, respectively, of uranium in spent fuel. The expected total volumes of conditioned waste from existing United Kingdom facilities to the end of their lives are 1.5×10^6 m^3 of low-level waste, 2.4×10^5 m^3 of intermediate-level waste and 1.5×10^3 m^3 of high-level waste [I38].

192. There are also currently five reprocessing facilities with a capacity of greater than 1 t/a undergoing decommissioning and two more for which decommissioning is planned [I34]. Information related to exposures from the decommissioning of such facilities is scarce and relates more to the level of compliance with regulatory constraints than to actual public exposure. While worker exposure may arise from dismantling, demolition and waste management operations, public exposure will depend on the criteria adopted for residual radioactivity at the site and on the transport of waste to disposal sites. The information available indicates that the exposure of the public due to decommissioning will be very low and will be constrained in the long term by national regulations regarding acceptable levels for residual radioactivity in recycled materials and in the environment. Estimates of doses due to waste rock and tailings were, however, included in the doses estimated for uranium mining and milling.

193. During the decommissioning of facilities, many materials may be recycled. Different criteria are being applied by different countries, but the information currently available is not sufficient to estimate the contribution from recycled materials to public exposure [B13, I19, I24, I40, L13].

(g) Summary of estimates of doses due to nuclear power production

194. The estimated doses to members of the public due to the generation of electrical energy by nuclear power are summarized in table 22. For local and regional population groups, a normalized factor of 0.27 man Sv/(GW a) has been determined. This is slightly lower than the value derived in the UNSCEAR 2000 Report [U3], 0.44 man Sv/(GW a). For all activities related to the production of energy, a normalized collective effective dose of 0.72 man Sv/(GW a) was determined. Using this coefficient, with an average of 278 GW(e)/a per year produced in the 1998–2002 period, an annual collective dose of about 200 man Sv is estimated for all operations related to energy production. The annual per caput doses to representative local and regional populations surrounding nuclear power installations are less than 10 μSv. The collective doses from globally dispersed radionuclides are delivered over very long periods and to an assumed "maximum" population of the world. If the practice of nuclear power production were limited to the next 100 years at the present capacity, the maximum annual per caput effective dose to the global population would be less than 0.2 μSv.

2. Transport of nuclear and radioactive material

195. This section describes exposures related to the "normal transport" of radioactive material. Normal transport refers to operations that occur without loss or damage to the package and without an accident involving conveyance. Events in which the shipment is not timely, the package or conveyance is damaged or the contents are lost or destroyed, are considered to be transport accidents or incidents [I20]. Accidents and incidents do occur during transport, but their consequences are normally limited by built-in safety features of the package together with the controls required for transport, including emergency response procedures [H28]. The consideration of accidents is outside the scope of this annex and is discussed in annex C, "Radiation exposures in accidents", of the UNSCEAR 2008 Report.

196. Radioactive materials of natural or artificial origin are used widely around the world and are transported within and between countries. A wide range of different materials are transported, from small quantities of radiopharmaceuticals for medical purposes to highly radioactive spent nuclear fuel and vitrified waste arising from the nuclear fuel cycle. The handling and transport of these radioactive materials can give rise to the radiation exposure of workers and of members of the public. In a lay sense, the term "public" is often taken to include transport workers (i.e. transport workers are often considered as a subset of the "public" who are generally exposed to the highest dose rates [V23]). However, in this annex, exposure of this group of workers will, whenever possible, be considered separately from the exposure of members of the general public, such as pedestrians, passengers and bystanders.

197. The data on numbers of packages are generally well known for nuclear fuel cycle operations, but for other transport operations the number can in most cases only be estimated. There is also a large variation between countries in the number of packages, because some countries have nuclear fuel cycle operations and some have major suppliers of radionuclides [H29]. The IAEA estimates that 10 million shipments of radioactive material are transported annually. Each shipment is made up of either a single package or a number of packages [I5]. The vast majority, some 95%, of these shipments are unrelated to the nuclear fuel cycle, only 5% being related to fuel cycle transport [W16].

198. Road, rail, air and sea transport are all commonly used for the transport of nuclear fuel cycle material, of radioactive material to be used in medicine, industry and research, and of waste. Air transport of nuclear fuel cycle material is carried out only to a limited extent [W14]. The available data indicate that exposures under normal conditions of transport are low. At least for the United Kingdom and the United States, the transport of fuel cycle material contributes significantly less to the exposure of transport workers than does the transport of non-fuel-cycle material [I5].

199. Mobile radiography sources are relatively numerous throughout the world. For example, there are about 850 in France, and about one half of these are transported daily by users from storage to their place of use. The transport dose for radiography operators due to these sources has not been included in this annex because of the difficulty in distinguishing between doses arising from the transport of radioactive material and doses resulting from the radiography operations themselves [C3, H4].

200. The number of fuel transports in Germany is shown in figure XXIV for the period 1994–2002. The number includes transports of irradiated and non-irradiated fuel and of waste by rail, road, sea and air. The overall number of transports decreased from 1994, reaching a minimum in about 1999, and started a relatively slow growth up to 2002. In 2002, the major contributor to the number of transports was the international transport of non-irradiated fuel by road, which accounted for nearly 50% of all nuclear fuel transports, with the international sea transport of non-irradiated fuel accounting for about 20% [B48].

(a) Transport by land routes

201. Most transport operations include the initial road transport from the production site to the railway station, airport, harbour or collection centre. During this part of the

journey, vehicles may pass through residential or crowded areas and along busy roads and highways. In certain places the pedestrian density may be unusually high, while in others there may be only people waiting at bus stops to represent the potentially exposed population. Passengers in vehicles near the delivery vehicle will also be exposed. Overall, the exposure of such members of the public is expected to be much lower than of the exposure of workers involved in actual transport and cargo operations. Collective doses will depend mainly on the population density along the transport route [V23]. Although it would appear that both collective and individual doses to the public are low [I5], data are scarce.

202. A survey was performed in Mumbai, India, regarding the carriage of radioactive material in "Type A" packages [I33] for use in medicine, industry and research; such material is supplied by the Bhabha Atomic Research Centre, Mumbai, to a large number of users all over India. Packages delivered to the air cargo terminal are ultimately sent to various parts of the country. Radiation doses to the urban public due to shipments of radioactive material are likely to be much greater in Mumbai than in any other city in India. Essentially it is the pedestrians and the passengers travelling in nearby vehicles who are exposed to radiation during the transport of radioactive material. The estimated radiation exposures were found to be low, but collective doses could theoretically be large because of the relatively high pedestrian and passenger density in Mumbai. Measured dose rates, used to estimate public exposure, ranged from 1 to 55 μGy/h for passengers in vehicles beside the delivery van and for pedestrians on sidewalks. The annual collective dose resulting from the transport of radioactive consignments in Mumbai was estimated to be about 0.1 man Sv [V23].

203. The collective doses accruing to the general public due to incident-free road transport of sealed spent sources generated by nuclear application institutes in India were estimated for the year 2001 [U43]. The main contribution to collective dose was due to the transport of decayed ^{192}Ir sources that had been used for industrial radiography, brachytherapy and nucleonic gauges, with a collective dose to both transport workers and to the public of about 46 man Sv.

204. Analysis of the shipments by road for the period 1987–2000 by authorized carriers in Italy concluded that doses mainly arise from transport operations associated with radioisotope supply and distribution, and with the transport of non-nuclear radioactive waste. Negligible doses arise from transport operations associated with the nuclear fuel cycle, because of the very small number of shipments of nuclear material. The greater part of the exposures to people due to the shipment of radioactive material for industrial and medical uses arises from transport for medical purposes, with an estimated maximum annual individual effective dose of 0.0012 mSv [C3].

205. In France, spent fuel is carried mainly by rail. Roads are used only between certain power plants and the nearest railway station, and then between the rail terminal and the La Hague reprocessing facility. Also, transport of waste between the various producers and the storage centre at La Hague is accomplished principally by rail and only partly by road. The contribution of waste transport to the irradiation of workers and the public remains very low. Members of the public residing along the (road and rail) transport routes or near the sites of storage in transit may receive doses due to the transport of radioactive material. The annual collective dose received by the public was estimated to be at most about 0.10–0.15 man Sv, about half of the dose received by workers [H4].

206. Collective doses were assessed for population groups in the vicinity of the transport routes within Germany and were related to the incident-free transport of radioactive material and spent fuel. The population groups outside nuclear facilities considered in this assessment included railway personnel in shunting yards, populations in the vicinity of shunting yards and rail routes, and railway passengers. Collective dose estimates for three types of spent fuel management are presented in table 23. Comparison with estimates for low-level waste showed that the main contributor to the collective dose for all population groups would be the transport of low-level waste from PWRs to the depository at Gorleben, which exceeded the exposure due to the transport of spent fuel from PWRs by two orders of magnitude. The transport of spent fuel accounts for less than 1% of the total dose. The annual dose to a hypothetical "critical group" passenger who passes every shipment of radioactive material from the reprocessing facility to the depository was estimated to be 0.08 mSv. Inhabitants who spend the entire year within a distance of 1 km from the railway track would receive a conservatively estimated annual dose of 0.03 mSv [B7].

207. A study was performed in the former German Democratic Republic related to an impact assessment of the transport of waste to the Endlager für radioaktive Abfälle Morsleben (ERAM), a former salt mine located in Saxony-Anhalt. After a temporary shutdown, ERAM restarted disposal operations in 1994. From then to the end of 1996, some 11,000 m^3 of waste, primarily low-level solid waste from operating nuclear power plants and from decommissioning, were delivered and placed in deep geological formations. The preferred mode of transport for waste shipments was rail, except for a small fraction of the journey within 40 km of the repository site. Estimates of annual doses to members of the public were generally less than 0.1 mSv [S12].

208. Some 500,000 packages of radioactive material are shipped annually within the United Kingdom by road and around 4,000 movements annually by rail. About 52,000 of these packages are shipped to and from hospitals; about 15% of these contain technetium generators. Doses to members of the public due to the transport of radioactive material tend to be very low. The estimated maximum individual doses were less than 20 μSv/a. The estimated collective dose to the public due to the movement of radioisotopes to and from

hospitals was 0.013 man Sv, with a further 0.005 man Sv due to exports. The estimated collective dose to the public due to the movement of spent nuclear fuel flasks within the United Kingdom was no more than about 0.001 man Sv [W7]. A study on the transport of NORM in the United Kingdom found that the annual dose to any member of the public from the shipment of any type of NORM would be much less than a microsievert [H30].

(b) Transport by sea

209. Spent fuel from Japan is transported by sea in dedicated vessels for reprocessing in Europe, arriving at sea terminals close to the reprocessing plants and then undergoing short road/rail journeys. Spent fuel flasks are handled by cranes at the sea terminals, with limited access by workers. Some spent fuel is likewise transported by sea from continental Europe to the United Kingdom. The limited transport of high-level waste, for example from La Hague in France to storage facilities elsewhere in Europe and in Japan, follows procedures similar to those for spent fuel transport [W14].

210. Non-irradiated nuclear fuel material (such as ores, concentrates and chemical derivatives) are shipped around the world in various types of container, while irradiated material is generally transported by special ships dedicated for this purpose. Packages containing radioactive material are usually carried in containers on board ships or in vans and lorries. The containers are usually loaded with material for the nuclear fuel cycle, while the vehicles usually carry packages of radionuclides for medical or general industrial use [B11].

211. In 1994 radioactive material was carried on some 1,100 voyages to, from or in transit through the United Kingdom. Of these voyages, about 55% were of nuclear fuel cycle material (50% non-irradiated and 5% irradiated), and the remaining 45% involved radionuclide consignments for medical and general industrial use. The carriage of nuclear fuel cycle material on freight vessels and dedicated ships leads to the possible exposure of the crew, a small number of passengers and dockworkers. The transport of packages containing radionuclides in vehicles on ferries may result in the exposure of both crew and passengers. Exposures to passengers are low, with annual individual doses unlikely to exceed 0.032 mSv [B11].

212. A study performed in Egypt assessed the exposure of populations living alongside the Suez Canal due to the intensive transport of radioactive material by ships passing through the canal. The quantities of radioactive material that potentially exposed coastal populations are presented in table 24. The estimated average annual collective doses to the public in the period 1986–1992 in the towns of Port Said, Ismailia and Suez are 4.11×10^{-8}, 3.01×10^{-8} and 5.04×10^{-8} man Sv, respectively. The transport of low-activity material, such as uranium (as U_3O_8), represented the largest contribution to the collective dose to the public within the Suez Canal area. Harbour workers, with an annual collective dose of about 3×10^{-4} man Sv, were the population group that received the largest individual doses [S1].

(c) Transport by air

213. A major producer of radionuclides for worldwide medical use is located in the United Kingdom. The radionuclides are packaged and then sent by road either for domestic delivery or for export via a number of airports. Packages containing radioactive material arrive at the airport in light trucks and are then unloaded and checked in the carrier's warehouses. The packages are sorted and grouped according to destination. The majority of packages transported by air are either excepted or Type A. Excepted packages have surface dose rates of less than 5 μSv/h. However, some Type A packages containing technetium generators have surface dose rates approaching 1 mSv/h. Measurements have indicated typical dose rates close to packages containing technetium generators of around 40 μSv/h, with surface dose rates of up to 800 μSv/h [W3].

214. An extensive survey on the routes, kinds of airplane, cargo operations, crew flight schedules and numbers of passengers was carried out in the United Kingdom in 2001. Aircrew and passengers may be exposed to packages stored in holds during flight. The number of packages transported by air in the United Kingdom in 2001 is shown in table 25. A number of the carriers stated that they did not consider "excepted" packages to be "radioactive material" and therefore exclude this category from package totals. For passengers, measured dose rates ranged from 0.5 to 9 μSv/h in the main cabin area, and from 4 to 15 μSv/h in the front seats. Half the passengers were exposed to dose rates of less than 1 μSv/h, and the average passenger dose rate was 3 μSv/h. No information was provided regarding frequent flyers and couriers, but it was considered that frequent flyers using short-haul flights (which have a Radioactive Traffic Factor of 1 in 475) are unlikely to receive a significant dose due to radioactive cargo [W3]. (The Radioactive Traffic Factor (RTF) is the ratio of flights carrying radioactive cargo to the total number of flights.) Estimates of collective doses due to air transport in the United Kingdom are presented in table 26.

(d) Summary on the exposure to radioactive material during transport

215. In general, doses to members of the public due to the normal transport of radioactive material are verifiably very low. Some results of initial surveys on this topic are presented in table 27. More recent surveys produced similar results (table 28). In Germany, the highest conservatively estimated annual dose to members of the public due to nuclear fuel shipments was typically less than 0.1 mSv. In France, these shipments are estimated to give rise to a maximum annual dose of 0.2 mSv, while shipments of waste at a

storage facility are estimated to give rise to a maximum annual dose of 0.12 mSv, and shipments by road could lead to an annual dose of up to 0.07 mSv owing to the vehicles waiting at traffic lights. In the Netherlands, the estimated maximum annual dose due to both nuclear and non-nuclear shipments was 0.02 mSv [I5]. More recent estimates predicted annual doses of less than 0.002 mSv for critical groups [E6]. In the United Kingdom, 0.02 mSv was the maximum annual dose estimated for sea and air passengers, while annual exposures due to road and rail transport were less than 0.01 mSv [I5].

3. Applications other than nuclear power

(a) Production of radioisotopes

216. Radioisotopes are widely used in industry, medicine and research. Radiation exposures may occur owing to trace amounts being released in production or at subsequent stages of the use or disposal of the radionuclide-containing products. For very-long-lived radionuclides, such as ^{14}C, all of the amount utilized may ultimately reach the environment. For short-lived radionuclides, such as most radiopharmaceuticals, radioactive decay prior to release is an essential consideration. The isotopes used most widely in medical examinations and nuclear medicine procedures are ^{131}I and ^{99m}Tc.

217. Estimates of doses resulting from radioisotope production and use are uncertain, owing to the limited availability of data on the commercial production of the radioisotopes and on the release fractions during production and use. The main radionuclides of interest are ^{3}H, ^{14}C, ^{125}I, ^{131}I and ^{133}Xe. The estimated annual collective effective dose due to radioisotope production and use is of the order of 100 man Sv [U6].

218. An important use of radionuclides is in medical diagnostic examinations and therapeutic treatments. Medical radioisotopes or their parent radionuclides can be produced in a reactor (by fission of uranium, e.g. ^{99}Mo, ^{131}I; or by activation, e.g. ^{59}Fe) or in a cyclotron (by nuclear reactions, e.g. ^{123}I, ^{201}Tl). The most important radioisotope, used in 80% of all diagnostic examinations, is ^{99m}Tc (from ^{99}Mo). In many countries the production, isolation and incorporation of the radioisotopes into generators, diagnostic kits or pharmaceuticals are often carried out in different facilities, which hampers quantification of the releases resulting from the overall production.

219. Limited data on ^{131}I releases from hospitals were cited in the UNSCEAR 1993 Report [U6]. There is high excretion of ^{131}I from patients following oral administration, but waste treatment systems with hold-up tanks are effective in reducing the amounts in liquid effluents to a small fraction (e.g. 5×10^{-4}) of the amounts administered to patients. This seems to be confirmed by the very low concentrations of ^{131}I measured in the surface waters and sewage systems of several countries [U6], although such information seems not to be systematically collected or reported.

220. With the global annual usage of ^{131}I in therapeutic treatments estimated at 600 TBq, a release fraction of 5×10^{-4} and a dose coefficient of 0.03 man Sv/TBq for ^{131}I released in liquid effluents (taken from annex A, "Dose assessment methodologies", of the UNSCEAR 2000 Report [U3]), the annual collective dose is estimated to be only 0.009 man Sv. The use of hold-up tanks should reduce the release of ^{99m}Tc, the other major radionuclide, to negligible levels as well.

221. In the United Kingdom, radioactive material, including radiolabelled materials for use in medicine, research and industry, is manufactured at two sites: Amersham and Cardiff. At Amersham, the total annual dose to critical groups in 2003 due to liquid discharges was assessed to be less than 5 μSv. Summing freshwater fish consumption and external exposure, doses to critical groups were estimated to be of the order of 5 μSv in 2003. The doses estimated for the critical group for terrestrial food were also less than 5 μSv in 2003. At Cardiff, the laboratory produces radiolabelled products containing ^{3}H and ^{14}C to be used in research and medical diagnostic kits. The dose to the most exposed group of seafood consumers was 24 μSv in 2003, including a contribution from external exposure. The hypothetical critical group for terrestrial foodstuffs comprised infants who ingested food produced on land conditioned by pelleted sludge from the wastewater treatment works. It was assessed that in 2003 the highest dose would have been less than 16 μSv, with doses from non-foodstuff pathways being less than 1 μSv [W6].

222. According to the results of a 2006 survey conducted by the IAEA, there were 246 cyclotrons operating in 39 IAEA Member States. The IAEA has estimated that worldwide there are about 300 cyclotrons currently operating that are involved in some aspect of radionuclide production. The number of cyclotron institutions that distribute radiopharmaceuticals, and in particular ^{18}F-labelled fluorodeoxyglucose (^{18}F FDG), is significant and growing [I37]. No information on public exposure due to the operation of cyclotrons has been found.

(b) Research reactors

223. Research reactors, given their wide variety of designs and modes of operation, as well as their wide range of uses, differ from reactors producing electrical energy. Research reactors are used for testing nuclear fuels and various materials, for investigations in nuclear and neutron physics, biology and medicine, and for the production of radioisotopes. The use of research reactors is globally much more widespread than the use of reactors for energy production. In 2003 there were 70 countries listed as having operated research reactors; among the 57 countries that still operate research reactors, there were 274 in operation; and 8 countries had a total of 10 research reactors under construction. The number of reactors is presented in figure XXV according to operational status and nominal power [I29].

224. Three sites in the United Kingdom—Dounreay, Harwell and Winfrith—house research reactors that have been or are in the process of being decommissioned. At Dounreay, the critical group of people who consumed food from the terrestrial environment was estimated to have received 6 μSv in 2003, which also includes a contribution from weapons test fallout. At Harwell, although there was no evidence that fish from the river were consumed, an assumed annual consumption rate of 1 kg was used in the dose assessment, leading to a dose estimate of 11 μSv for 2003. The dose to the critical group of local consumers from gaseous discharges was estimated to be less than 5 μSv. Doses estimated for Winfrith are of similar magnitude [W6].

(c) Consumer products

225. A number of products bought for everyday use contain low levels of radionuclides. Some of these items contain low levels of NORM, but the majority of consumer products containing radioactive substances have had the radioactive material deliberately added in order to make use of its chemical and radioactive properties. Historically the most significant radionuclide for use in radioluminous consumer products was ^{226}Ra. However, production of items luminized with radium ceased a few decades ago, with radium being replaced by ^{147}Pm and ^{3}H because these radionuclides are less radiotoxic. For timepieces containing tritium compounds, some leakage of the radioactive source may occur, because tritium is very mobile. Tritium emits only very weak beta radiation that cannot penetrate the skin, so that it contributes to the effective dose only when the tritium has entered the body [W6].

226. Ionization chamber smoke detectors are used to give an early warning of fire. Modern smoke detectors contain a small foil of ^{241}Am with an activity of not greater than 40,000 Bq. The dose rate at a distance of 2 m from a detector is about 2.4×10^{-5} μSv/h, assuming that the detector contains the maximum amount of activity. In the United Kingdom, about 80% of homes have a smoke detector fitted. Assuming an exposure of 8 h/d at a distance of 2 m from the detector results in an estimated annual dose of 0.07 μSv [W6].

227. Glass to which uranium is added to produce a yellow or green colour is called Vaseline glass. It was very popular in the 1800s and is still produced in the United States and the Czech Republic. The gamma dose rate close to the surface of the glass item is very low and was measured as less than 0.1 μSv/h. A typical surface dose rate due to beta radiation was 15 μSv/h, while the beta doses measured a few centimetres from the surface were negligible. Individual doses for some collections of uranium glass could be up to 0.5 mSv annually. However, for a large collection with a range of items, a typical maximum dose would be an order of magnitude lower. Uranium salts have also been used in the glaze on ceramic products such as tableware and tiles. They were also used as a colourant in ceramic tableware produced in the 1930s and 1940s in the United States. These items may now be found on collectors' markets. It was found that handling such items may give rise to very low levels of contamination on the skin, and the use of this tableware for eating could lead to very low ingestion doses [W6].

228. Some members of the public have collections of fossils, rocks or minerals. In some parts of the United Kingdom the native rocks contain significant concentrations of uranium and its decay products. The overall dose from such specimens under normal conditions of handling and display are only a small fraction of the overall dose from natural radiation. Photographic lenses used to have ^{232}Th added to them in order to increase the refractive index. Photographers carrying a camera with such lenses around the neck for several hours a day on many days of the year could receive an annual effective dose of a few hundred microsieverts. Currently these lenses are out of use in United Kingdom. A summary of doses associated with exposure to consumer products is presented in table 29 [W6].

229. The United States Nuclear Regulatory Commission (NRC) has assessed the potential individual and collective (population) radiation doses associated with selected products containing "by-product" material[2] [U35]. The dose assessments were in general based on reasonable assumptions, although in some cases the NRC noted that there was an absence of reliable data on the actual use of the products by individuals either in the workplace or elsewhere. The estimates reported are for effective dose equivalent to the average member of the critical group. The individual and collective dose estimates discussed here are restricted to doses estimated for the normal life cycle of a particular product or material, covering distribution and transport, intended or expected routine use, and disposal occurring over a 1 year time period. Actual or expected quantities of radioactive material in products and materials, when known, were used for estimating doses; otherwise, a value was used equal to the maximum allowed under the United States legislation on exempted quantities.

230. The estimates of individual doses incurred annually during the normal life cycle of a product or material associated with the current exemptions for by-product material in the United States ranged from less than 1×10^{-5} mSv to 0.2 mSv. A summary of individual effective doses from by-products in the United States is presented in table 30. The estimated individual doses were equal to or greater than 0.1 mSv annually for two products: *(a)* instruments used for measuring ionizing radiation that contain by-product material, with an estimated annual dose of 0.2 mSv received by a laboratory technician working with a bench-top instrument; and *(b)* spark gap irradiators containing ^{60}Co, with an estimated annual dose of 0.1 mSv received by a maintenance worker installing and maintaining spark gap irradiators.

[2] By-product material here includes any radioactive material associated with the operation of nuclear reactors, except for the source material for nuclear fuel and the special nuclear material which constitutes the fuel in a reactor. Source material is the raw material from which nuclear fuel is made; it includes uranium or thorium in their natural isotopic abundances.

231. The estimates of collective dose incurred during the normal life cycle of these products ranged from 0.1 to 40 man Sv for 1 year's distribution of products. For two categories of products, the estimated collective doses were equal to or greater than 10 man Sv: *(a)* the collective dose arising from the use of timepieces with hands or dials containing ^{3}H or ^{147}Pm was estimated to be 40 man Sv, which was incurred mainly because of the large number of individuals who wear such timepieces (wristwatches); *(b)* the collective dose arising from the use of electron tubes containing by-product material was estimated to be 10 man Sv over the tubes' useful lifetime of 10 years. In this case, most of the collective dose would result because of the large number of people exposed to radiation from electron tubes in the home and workplace. However, individual doses are normally very low, usually less than 0.1 mSv/a.

232. The estimates of individual doses incurred annually during the normal life cycle of a product or material associated with the current use for source material ranged from less than 1×10^{-5} mSv to 40 mSv. The estimated annual individual doses exceed 10 mSv for the following two cases (table 30): *(a)* chemical mixtures, compounds, solutions or alloys containing less than 0.05% by weight source material; and *(b)* rare earth metals and compounds, mixtures and products containing not more than 0.25% by weight source material. The high estimates in these cases result from the large volumes of exempted material present in workplaces and the high concentrations of uranium and thorium in this material. These estimated doses would be reduced substantially for the case of the workers using respiratory protection.

233. The estimated annual individual doses were equal to or greater than 1 mSv but less than 10 mSv for three materials: *(a)* for unrefined and unprocessed ore containing source material, the estimated dose of 3 mSv/a to a truck driver results from the large volume of exempted material that is handled and the relatively high concentration of uranium in the material; *(b)* for incandescent gas mantles, the estimated annual dose to a person using only gas lanterns for light would be 2 mSv and that to an individual who uses portable camping lanterns would be 0.1 mSv; *(c)* for welding rods containing thorium, the estimated annual dose of 8 mSv to a dedicated grinder of welding rods probably represents an unusual situation that would occur only at construction sites where many welders are employed.

234. The estimates of collective dose incurred during the normal life cycle of a product or material associated with the current exemptions in the United States for source material ranged from 0.001 man Sv to 700 man Sv for 1 year's distribution. There are five situations for which collective dose estimates are equal to or greater than 100 man Sv: *(a)* for chemical mixtures, compounds, solutions or alloys containing less than 0.05% by weight source material, the collective dose is a combination of estimated doses due to the use of ophthalmic glass, doses due the use of phosphate slag for building construction, and doses to future on-site residents from the disposal of coal ash, phosphate slag and water treatment sludge; *(b)* for incandescent gas mantles, the users of portable camping lanterns contribute most to the collective dose. The current trend towards the use of gas mantles not containing thorium and the use of other lighting devices should significantly reduce this collective dose estimate; *(c)* for welding rods containing thorium, the collective dose estimate is 300 man Sv, although this is predominantly received by professional welders over a 1 year time period, and only a fraction of it can be related to public exposure; *(d)* for glassware, the dose due to the display of large numbers of items (in homes and museums) contributes to the collective dose; *(e)* for thorium in finished optical lenses, the estimated doses to users of 35 mm photographic cameras contribute most of the collective dose.

235. There are also two situations where the collective doses were equal to or greater than 10 man Sv but less than 100 man Sv: *(a)* for rare earth metals and compounds, mixtures and products, the contributors to collective dose are bastnaesite and cerium concentrates (industrial workers), television faceplates and waste disposal (future on-site residents at landfills); *(b)* for glazed ceramic tableware, the estimated doses are due to the display of large numbers of items (in homes and museums).

(d) Other sources of public exposure

236. Estimated potential annual doses from exposures at hospitals, institutions of higher education and other research laboratories where radioactive material is used in the United Kingdom ranged from 0.02 to 13 μSv. The highest annual dose estimated for an industrial site was 170 μSv, but the calculation assumed authorized discharge levels as opposed to actual discharge levels, which are generally much lower. Landfill sites may also give rise to exposure of members of the public. Doses in 2003 to the critical group of people who live close to the Drigg disposal facility in the United Kingdom were 46 μSv (including components due to deposits from the Chernobyl accident and to weapons tests fallout). Low levels of radioactive material may be disposed of at some landfill sites. It is estimated that the annual dose incurred by ingesting water containing a leachate arising from a landfill that accepts ^{125}I in waste would be 5 μSv. Tritium has also been detected near some landfill sites. A person drinking water from a nearby borehole with about 1,000 Bq/L would receive an annual dose of less than 12 μSv [W6].

237. The use of radioactive substances in an unsealed form is widespread in medicine. These substances are employed in nuclear medicine and radiotherapy departments for medical diagnosis and for treating cancers and other diseases with internal irradiation, and also in clinical biology and medical research laboratories. These uses result in significant volumes of radioactive waste, only a small part of which is transferred to specialist radioactive waste processing centres, while the major part is stored on the site until the activity has decreased to a level allowing the waste to be treated

as normal hospital waste. In view of the large number of establishments and departments involved and the multiple ways of managing the waste, regulatory systems have been put in place. However, chance incidents, such as the discovery of radium needles or radioactive waste in areas normally accessible to the public, or of quantities of radioactive iodine in river waters, although without consequences for public health, have nevertheless alarmed the general public [E12].

238. "Orphan radioactive source" is a term utilized by nuclear regulators to denote radioactive sources that are outside official regulatory control. Orphan sources include: sources that were never subject to regulatory control; sources that were subject to regulatory control but have since been abandoned, lost or misplaced; and sources that were stolen or removed without proper authorization. Exactly how many orphan sources there are in the world is not known, but the numbers are thought to be in the thousands. The NRC reports that United States companies have lost track of nearly 1,500 radioactive sources within the country since 1996, and more than half have never been recovered. A European Union study estimated that every year up to about 70 sources are lost from regulatory control within the Union. Although the majority of these sources would not pose a significant radiological risk, the risk of accidents is the major concern arising from orphan sources. Sealed sources or their containers can be attractive to scavengers for the scrap metal trade because they appear to be made of valuable metals and may not display a radiation warning label. Cases where unsuspecting people or even members of the public have tampered with sources have led to serious injury and in some cases death. Some of the more notable such accidents are described in annex C of the present report.

239. Orphan sources are a widespread phenomenon in the Newly Independent States (NIS) of the former Soviet Union. For example, a legacy of Georgia's sharp economic decline after the break-up of the Soviet Union was a loss of control over radioactive sources used in industry. The collection and sale of scrap metal from abandoned factories has provided a means of livelihood for some persons, and some orphan sources have been found in shipments of scrap. Not all the incidents reflect deliberate attempts to steal radioactive sources. The great majority of the trafficking incidents detected appear to involve opportunists or unsophisticated criminals motivated by the hope of profit. In some cases, the theft of sources was incidental to the theft of vehicles. As many as 300 radioactive sources have been recovered in Georgia since the mid-1990s, and these sources have caused at least one death and many injuries to the public. In 2006, two abandoned and potentially dangerous radioactive devices were successfully secured, one in the village of Iri, where background radiation levels were elevated to 12 times above normal in the village centre, and the other in the village of Likhaura. The radioisotope in both sources was ^{137}Cs. In Moldova, several large devices containing about 130 TBq (3,500 Ci) of powdered ^{137}Cs chloride used for agricultural purposes in the former Soviet Union were found abandoned or stored in precarious conditions [G13, I36, W8].

4. Summary on exposures due to peaceful uses of man-made sources of radiation

240. A summary of dose estimates related to public exposures due to peaceful uses of man-made sources of ionizing radiation is presented in table 31. Currently available information does not allow estimates of global doses to be made, although individual doses are very low for sources unrelated to nuclear power production. Although individual doses may be up to a few millisieverts per year for specific population groups, in connection with some specific practices and exposure scenarios, the worldwide average annual per caput dose is of the order of microsieverts.

D. Use of man-made sources for military purposes

1. Nuclear tests

(a) Global fallout

241. Nuclear test explosions in the atmosphere were carried out at a number of sites, mostly located in the northern hemisphere, between 1945 and 1980. The periods of most active testing were 1952–1958 and 1961–1962. In all, 502 atmospheric tests, with a total fission and fusion yield of 440 Mt, were conducted. The number and yields of worldwide atmospheric nuclear explosions as estimated by UNSCEAR [U3] are summarized in table 32 and figure XXVI. After the Treaty Banning Nuclear Weapon Tests in the Atmosphere, in Outer Space and Under Water was signed in Moscow on 5 August 1963, nuclear test explosions were mostly conducted underground [I9]. A summary of all atmospheric and underground nuclear weapons tests by country is presented in table 33. Besides these, there were 39 safety tests that took place above ground, in which more or less fully developed nuclear devices were subjected to simulated accident conditions (i.e. the nuclear weapon cores were destroyed by means of conventional explosives, with no or very small releases of fission energy) [I12].

242. The earlier atmospheric tests remain the principal source of current radiation exposure worldwide due to nuclear weapons testing. Table 34 provides estimates of the activity of radionuclides released and globally dispersed in all atmospheric nuclear tests [U3]. Radioactive debris from an atmospheric nuclear test is partitioned between the local ground or water surface and the tropospheric and stratospheric regions, depending on the type of test, the location and the yield. The subsequent precipitation of the debris and its deposit on to the earth is termed "local fallout" when deposited locally, and "tropospheric fallout" and "stratospheric fallout" when deposited globally [I9].

243. Local fallout can contain as much as 50% of the total fallout produced in the case of above-ground tests, and includes large radioactive aerosol particles that are deposited within about 100 km of the test site. Tropospheric fallout consists of smaller aerosols that are not carried across the

tropopause after the explosion and that deposit with a mean residence time in the atmosphere of up to 30 days. During this period the debris becomes dispersed, although not well mixed, in the latitude band of the initial injection and following trajectories governed by wind patterns. From the viewpoint of human exposure, tropospheric fallout is important for nuclides with half-lives of a few days to two months, such as ^{131}I, ^{140}Ba and ^{89}Sr.

244. Stratospheric fallout, which makes up a large part of the total fallout, consists of those particles that are carried up into the stratosphere, disperse and later give rise to worldwide fallout, the major part of which occurs in the hemisphere of the initial injection. Stratospheric fallout accounts for most of the worldwide residues of long-lived fission products. The exposure of humans to fallout comprises internal irradiation (inhalation of radioactive material in surface air and ingestion of contaminated foodstuffs) and external irradiation from radioactive material present in surface air or deposited on the ground [I9]. Atmospheric processes related to dispersion and deposition of nuclear test fallout were comprehensively reviewed in the UNSCEAR 2000 Report [U3].

(i) Doses from global fallout

245. The basic input for calculations of doses due to fallout radionuclides has been the measured deposition density of ^{90}Sr. The measured annual hemispheric deposition for representative middle-latitude sites is given in table 35. General procedures for deriving dose estimates from the measured or calculated deposition densities of radionuclides were described in detail in reference [U3], and only a summary of the main conclusions from previous reports will be presented here for completeness.

246. Estimates of the total annual effective doses due to radionuclides produced in atmospheric nuclear testing are summarized in table 36, and the variation with time of the average per caput effective doses from nuclear weapons fallout is presented in figure XXVII. These results are for the average deposition of fallout radionuclides weighted according to hemisphere and the world population. Doses for specific regions of the world can be obtained by adjusting these results for the latitudinal distribution of deposition determined from ^{90}Sr measurements.

247. The estimated global average annual per caput effective dose due to atmospheric nuclear weapons testing was highest in 1963 (0.11 mSv) and subsequently declined to less than 0.005 mSv in the 2000s. External exposure generally made the largest contribution to annual doses; initially it was due to short-lived radionuclides and subsequently to ^{137}Cs. The annual doses at present are due almost equally to external exposure (53%) and internal exposure due to ingestion (47%). The dose from ^{14}C (30% of the total) now exceeds that from ingestion of other radionuclides [U3].

248. The short-lived radionuclide ^{95}Zr (with its decay product ^{95}Nb) was the main contributor to external exposure during active testing. Of the radionuclides contributing to external exposure, only ^{137}Cs has a half-life of greater than a few years, thus it became the most important contributor to annual doses after approximately 1966. At present it is the only radionuclide contributing to continuing external exposure from deposited radionuclides.

249. Several radionuclides contribute to exposure via the ingestion pathway. For the short-lived radionuclides (^{131}I, ^{140}Ba, ^{89}Sr), the exposures occur within weeks or months following deposition. Further exposure via ingestion of longer-lived radionuclides comes from ^{55}Fe and the transuranic elements. Committed doses due to the transuranic radionuclides are very low and the contributions to annual doses negligible. During active testing, ^{137}Cs was the most significant component, owing to its more immediate transfer to diet and subsequent delivery of dose. Because of the continuing transfer of the long-lived ^{90}Sr to diet, as well as the longer retention of ^{90}Sr in the body, this radionuclide became the most important contributor to dose beginning in about 1967. The short-lived radionuclides have been relatively insignificant contributors to ingestion exposure. Important contributors to inhalation exposure were ^{144}Ce, the transuranic radionuclides, ^{106}Ru, ^{91}Y, ^{95}Zr and ^{89}Sr. Deposition (and thus concentrations of these radionuclides in air) decreased rapidly after atmospheric testing ceased in 1980. Even for the long-lived transuranic radionuclides, inhalation exposure became insignificant after 1985.

250. One further contribution to the annual exposure comes from the globally dispersed radionuclides ^{3}H and ^{14}C. For both radionuclides, there is no external exposure component and only negligible exposure from inhalation; exposure arises almost entirely from ingestion. The long-lived radioisotope ^{14}C is the dominant contributor, accounting for 70% of the total effective dose commitment to the world population. However, if only 10% of the ^{14}C dose commitment is included in the comparison, i.e. if dose commitments are truncated approximately to the year 2200 (by which time all other radionuclides will have delivered effectively all of their doses), ^{14}C contributes only 19% to the truncated effective dose commitment to the world population. About one quarter of the collective dose will have been delivered by the year 2200. The global estimates include a contribution from the doses to people close to the sites used for atmospheric tests. Although this contribution is small in global terms, some local doses were substantial [I9].

(ii) Local and regional exposures

251. Local fallout can constitute as much as 50% of the total produced by surface tests and includes large radioactive aerosol particles that are deposited within about 100 km of the test site [I9]. A summary of the estimated yields in different atmospheric layers was shown in figure XXVI. Since atmospheric nuclear weapons tests were conducted in

relatively remote areas, the exposures of local populations did not contribute significantly to the global collective dose from this practice. Nevertheless, individuals living downwind of the test sites received higher doses than average.

252. Areas within a few hundred kilometres of the test site are generally designated as "local" and those within a few thousand kilometres as "regional". A detailed description of the main characteristics of all tests can be found in reference [U3]. The locations of the main test sites are shown in figure XXVIII.

253. *Nevada test site (United States test site).* The Nevada Test Site (NTS) in the United States was the location for 86 atmospheric nuclear tests, carried out from 1951 to 1962. In addition, 38 of the approximately 800 underground tests involved releases of radioactive material. Although small in comparison with releases from the atmospheric tests, they were sufficient to be detected off-site [S22]. Additional cratering tests also injected debris into the atmosphere. Relatively few underground tests led to releases that affected local areas [U3].

254. Estimates of external exposures due to atmospheric tests at the NTS were derived from survey meter and film badge measurements for 300 communities in the local areas (at distances of less than 300 km) around the test site in Nevada and in south-western Utah. The effective dose exceeded 3 mSv in 20% of the population of 180,000. The highest effective doses were in the range 60–90 mSv; the population-weighted average was 2.8 mSv. Exposures resulted primarily from short-lived gamma emitters (with half-lives of less than 100 days). The collective external whole-body dose within the 300 km closest to the NTS was about 500 man Gy, and 12,000 man Gy for the area within about 800 km of the test area [S22], arising primarily from the exposure of areas with large populations.

255. Internal exposures resulting from atmospheric testing at the NTS were estimated from deposition measurements using an environmental transfer model. Absorbed doses to organs and tissues from internal exposure were substantially less than those from external exposure, with the exception of the thyroid, to which ^{131}I from the ingestion of milk contributed relatively higher doses. Estimates of absorbed doses to the thyroid in 3,545 locally exposed individuals ranged from 0 to 4.6 Gy, with an average of 0.098 Gy. Mean thyroid doses for residents of Utah, Nevada and Arizona were estimated to be 0.17, 0.05 and 0.012 Gy, respectively [U3].

256. *Bikini and Enewetak Atolls, Marshall Islands (United States test sites).* In 1946, Bikini Atoll was the first site in the Marshall Islands to be used for nuclear weapons testing by the United States. In 1948, Eniwetok, a neighbouring atoll, replaced Bikini as the test site. In 1954, Bikini was reactivated as a test site and was used until nuclear weapons testing in the Marshall Islands was ended in 1958. Bikini Atoll was the site of 23 of the 66 tests, which were conducted under water, at ground level and above ground. The yields of the tests at Bikini Atoll amounted to about 72% of the total yield for the two test sites in the Marshall Islands.

257. Bikini Atoll, located 850 km north-west of the capital of the Marshall Islands, Majuro, comprises more than 23 islands and islets. Bikini, Eneu, Nam and Enidrik Islands account for over 70% of the land area. Bikini and Eneu are the only islands of the atoll that have had a permanent population. Before nuclear weapons testing started, the population of Bikini Atoll (at that time 167 people) was evacuated and resettled.

258. The test resulting in the most significant local exposures was the thermonuclear test Castle Bravo on 1 March 1954 at Bikini Atoll. Unexpectedly heavy local fallout occurred east of the atoll owing to a sudden and unusual change in wind direction, predominantly from the west rather than the east, on the day of the test, and an unexpected increase in fission yield. High radiation doses were received by the inhabitants of Rongelap Island (67 persons, including three in utero), about 210 km from Bikini Atoll, and by some Rongelap islanders temporarily residing on Ailinginae Atoll, about 150 km away (19 persons, including one in utero). Further east, exposures occurred at Rongerik Atoll (28 United States servicemen) and Utirik Atoll (167 persons, including eight in utero). These individuals were evacuated within a few days of the initial exposures [I9, U3].

259. Effective doses as a result of external exposures, mainly from short-lived radionuclides, ranged from 1.9 Sv on Rongelap Island and 1.1 Sv on nearby Ailinginae Atoll to 0.1 Sv on Utirik Atoll. The collective effective dose was about 160 man Sv [I9]. Equivalent doses to the thyroid, caused by several isotopes of iodine and tellurium and by external gamma radiation, were estimated to be 12, 22 and 52 Sv on average, and 42, 82 and 200 Sv maximum, to adults, nine-year-old and one-year-old children, respectively, on Rongelap Island. Exposures due to residual radiation on Utirik and Rongelap Atolls of residents who returned to these islands in 1954 and 1957, respectively, were of the order of 20–30 mSv from external irradiation and 20–140 mSv from internal exposure over the subsequent 20-year period.

260. External exposure of the servicemen on Rongerik Atoll due to the Castle Bravo test was 0.8 Sv. The Japanese fishing vessel Lucky Dragon was also in this area at the time of the test, and 23 fishermen were exposed. Their external exposures from fallout deposition on deck ranged from 1.7 to 6 Sv, mostly received on the first day of the fallout but continuing for 14 days until the ship returned to its port. Thyroid doses to these fishermen were estimated at 0.2–1.2 Gy due to ^{131}I on the basis of external counting; however, since other short-lived iodine isotopes were also present, total doses to the thyroid due to inhalation over a period of five hours were estimated to have been 0.8–4.5 Gy [U3].

261. No other tests seem to have resulted in significant exposures to the population in the Pacific region, even

though press and other official spectators did observe the two Crossroads explosions, in 1946, from relatively short distances. Military and test personnel probably received some exposure from handling radioactive debris during clean-up operations [S22].

262. In 1968, following radiological surveys that had been carried out since 1958, resettlement of the Bikinian people on the atoll was approved, and in 1969 the atoll was cleared of debris. Fruit trees, including coconut, breadfruit, pandanus, papaya and banana, were replanted. Eventually, 139 Bikinians resettled there. Further radiation survey and sampling programmes showed, in 1978, a tenfold increase in the body content of ^{137}Cs for the inhabitants of Bikini Atoll; this was mainly due to increased consumption of coconut fluid for lack of adequate supplies of freshwater. In response to the high uptake of caesium in the population, the residents were again relocated [I9]. During the temporary resettlement of Bikini Atoll from 1971 to 1978, total whole-body exposures were estimated at 2–3 mSv/a [U3].

263. *Johnston Island (United States test site).* The United States used Johnston Atoll, located about 1,330 km south-west of Honolulu, Hawaii, as a launch site for 12 high-altitude nuclear tests beginning in 1958. All tests were intended as airbursts, but three resulted in unintended non-nuclear destruction that led to contamination of the atoll with radioactive debris. The contamination was primarily in the form of particulate debris, much of it being metal from the rockets accompanied by considerable amounts of fissionable plutonium and/or uranium.

264. The atoll had been a United States military installation for several decades and currently is a wildlife sanctuary. There is no evidence of native populations ever having lived on the atoll, and certainly none were present during the years of nuclear testing. Hence there is no evidence that members of the public within the immediate region were exposed to the radioactive debris from the aborted tests. The nine successful tests, because of their large yields and high altitude of detonation, contributed mostly to global fallout, as the closest populated islands would have been those of Hawaii [S22].

265. *Amchitka Island (United States test site).* The three tests on Amchitka Island, Alaska, represent 15–16% of the total effective energy released during the United States underground nuclear testing programme from 1951 to 1992. Long Shot was detonated at a depth of 716 m in 1965, Milrow was detonated at a depth of 1,220 m in 1969, and Cannikin, the largest United States underground nuclear test, was detonated at a depth of 1,790 m in 1971 [D2].

266. *Christmas Island and Malden Islands, Kiribati (United States and United Kingdom test sites).* Christmas Island and the Malden Islands in Oceania were used by the United States and the United Kingdom for testing nuclear devices. Both islands are now part of the Republic of Kiribati. The land area of Christmas Island is about 390 km^2 and its 1990 population was about 2,500. There were six British nuclear tests on Christmas Island in the period 1957–1958 and 24 United States tests in 1962 in the vicinity of the island [H7].

267. Nearby Malden Island is an uninhabited atoll today, and has been so since the British occupation in 1956. There were three British nuclear tests near Malden Island. The tests in the Pacific at Malden Island and the Christmas Islands were airbursts over the ocean or explosions of devices suspended from balloons at 300–450 m over land [U3]. Local fallout would have been minimal following these tests. Little or no information is available on exposure of the public or of civilian test personnel at either site, although Fijian troops that participated in the tests and afterwards were involved in clean-up operations made claims related to these events [S22].

268. *Monte Bello, Emu and Maralinga, Australia (United Kingdom test sites).* The United Kingdom nuclear weapons testing programme included 21 atmospheric tests at sites in Australia and the Pacific. Twelve tests were conducted between 1952 and 1957 at three sites in Australia: the Monte Bello Islands, Emu and Maralinga. The Maralinga tests included seven nuclear explosions and hundreds of minor trials involving chemically generated explosions of radioactive material. Tests conducted at the Emu site, about 200 km north of Maralinga included two nuclear explosions and five smaller-scale experiments in 1953. These tests in continental Australia led to residual radioactive contamination of the two areas, covering some hundreds of square kilometres in total [H7]. These were mainly surface tests, with yields of 60 kt or less. Trajectories of the radioactive cloud were determined for each of these tests, and local and countrywide monitoring of air and deposition were performed.

269. Estimates of local external exposures were not made for the earlier tests; for the tests in 1956 and 1957, the external effective doses were less than 1 mSv. The numbers for local populations were not indicated [U3]. Estimates of internal exposures were also made for the overall Australian population. The average effective dose was 70 μSv, 83% of which was due to internal exposures, and the collective effective dose was 700 man Sv for the overall population of Australia [S22]. A number of safety tests conducted at the Maralinga and Emu sites in South Australia resulted in the dispersion of ^{239}Pu over some hundreds of square kilometres [U3].

270. *Semipalatinsk, Kazakhstan (Soviet test site).* The Semipalatinsk test site is located in the north-east corner of Kazakhstan, 800 km north of the former capital Almaty, 400 km east of the present capital Astana and about 200 km south-west of the border with the Russian region of Altai. At this site, 456 nuclear tests were conducted, including 86 atmospheric and 30 surface tests. Five of the surface tests were not successful and resulted in dispersion of plutonium in the environment. The site covers about 19,000 km^2. The local populations most affected lived

mainly in the Semipalatinsk region of Kazakhstan (now part of the Ust-Kamenogorsk region of Kazakhstan) and the Altai region of the Russian Federation, east and north-east of the test site. Traces of radioactive contamination were also found in southerly and south-easterly directions after some tests [S22, U3].

271. The earliest tests were above ground (atmospheric and surface) and were carried out in the northern technical area Š. The centre of the first (surface) explosion historically is referred to as "Ground Zero". The 340 underground tests were conducted in widely separated technical areas in the south (between 1961 and 1989) and east (from 1968 to 1989). This total includes four cratering nuclear explosions where the explosive charge was placed at a shallow depth below ground. Chagan was the first and largest of these tests. It resulted in a lake about 0.5 km in diameter and 100 m deep, with cliffs up to 100 m high, called Lake Balapan, or the "Atomic Lake". A much smaller lake was formed by the Tel'kem-2 test. Of the tests carried out deep underground, 13 resulted in the release of radioactive gases to the atmosphere.

272. The only settlements within the nuclear test site during the 40-year test period were the town of Kurchatov, north of technical area Š (built for servicing the test site), and the small settlements of Akzhar and Moldari along its northern edge. Two tests led to the most significant exposures of the population of Kazakhstan: the first test, on 29 August 1949, and the first thermonuclear test, on 12 August 1953. These and two additional tests (24 September 1951 and 24 August 1956) are stated to have contributed 85% of the total collective effective dose from all tests combined. The accumulated effective doses for several districts were in the range 0.04–2.4 Sv. The collective effective dose for ten districts was estimated to be 3,000–4,000 man Sv. Representative average doses for seven villages close to the site (in Kazakhstan) were estimated to be 0.2–900 mGy for whole-body exposure and 0.3–3.8 Gy for thyroid exposure. Absorbed dose to the thyroid from ingestion of radioiodines is quite uncertain, but may have been as high as 8 Gy for children in the Akbulak settlement [I10, S22, U3].

273. *Novaya Zemlya, Russian Federation (Soviet test sites).* Novaya Zemlya is an island located at the most northerly edge of Europe. Soviet testing on Novaya Zemlya began in 1955. Novaya Zemlya was the site of the world's largest nuclear weapons test, a 50 Mt detonation at an altitude of about 3.5 km. In all, 91 atmospheric nuclear tests took place on Novaya Zemlya, and tests performed on the island account for about one half of the total energy yield of all nuclear tests carried out in the entire world. Only one test, in 1957, was conducted directly on the ground surface. In addition, there were two tests on the water surface and three tests under water at the site. There were also 17 underground tests that vented, in most cases resulting in on-site contamination only.

274. The nearest village, Amderma, is 280 km away, and the much larger population centre of Arkhangelsk is approximately 1,000 km away. Three villages lie at intermediate distances [S22]. Very little information is publicly available concerning the local doses resulting from those tests. It is likely, however, that doses to local residents were relatively low, as most of the atmospheric devices were exploded at high altitude so that the expanding fireballs did not touch the ground surface. Preliminary information has been presented in the open literature concerning external radiation doses at the regional scale. The average external dose for the population of the eastern part of the Russian Federation (35 million) due to regional fallout in the years 1955–2000 is about 1 mSv [L24]. Concerning ingestion exposure, it is known that ^{137}Cs is abundant in lichen, reindeer and other environmental media. The ^{137}Cs concentrations in reindeer meat are much greater than those in milk, fish, geese or ducks, and reindeer herders are likely to receive much higher internal doses than the urban residents in the area, who consume reindeer meat only occasionally. The estimated internal dose due to ^{137}Cs (and to a lesser extent to ^{90}Sr) for reindeer herders has averaged about 1 mSv annually since the early 1960s; average annual doses to urban residents are estimated to be lower by a factor of 100.

275. *Kapustin Yar, Russian Federation–Kazakhstan (Soviet test site).* Kapustin Yar is located 250 km north-west of the Caspian Sea. Soviet testing at Kapustin Yar began in 1957. In all, 10 atmospheric nuclear tests took place at Kapustin Yar over six years. Very little information is publicly available about exposures resulting from the nuclear tests launched from Kapustin Yar. All the Kapustin Yar tests were high-altitude explosions (10.4–300 km), which in general contribute more to global fallout than to local fallout [L25, S22].

276. *Reganne and In Ecker, Algeria (French test sites).* Between 1960 and 1966, France conducted a series of four atmospheric and 13 underground nuclear tests at Reganne and In-Ecker, remote sites located in the south of Algeria. The French nuclear testing programme began with four low-yield surface tests in 1960 and 1961 at a site near Reganne in the Algerian Sahara, about 50 km south-east of Reganne (a village/oasis of a few thousand inhabitants) and about 150 km south of Adrar, a city with approximately 50,000 inhabitants. No information was found regarding local exposures following these tests. It is claimed that 15 people were probably contaminated when radioactive vapour and aerosol escaped through a fissure in the rock during a test in May 1962 that was performed under adverse wind conditions. Nine soldiers received about 600 mSv, mainly due to external irradiation (>90%) [S22, U3]. No early radiological or clinical effects were observed [B12]. Some residual contamination remains at both this site and a nearby site, In-Ecker, where 13 underground tests were conducted. Small quantities of plutonium were dispersed at these sites from safety experiments, which involved conventional explosives only. No information has been located on estimates of doses to the public from the tests conducted in Algeria by France [I32].

277. *Mururoa and Fangataufa (French test sites).* The Mururoa and Fangataufa Atolls in French Polynesia, situated

in the South Pacific Ocean, have evolved from extinct submarine volcanoes, and each rests upon a massive igneous volcanic basalt substratum capped by a sedimentary carbonate coral reef platform hundreds of metres thick and surrounded by ocean water thousands of metres deep. France conducted 193 nuclear experiments above and beneath the atolls of Mururoa and Fangataufa between July 1966 and January 1996. Of these, 178 were nuclear tests, in which nuclear devices were exploded with large releases of fission energy, and 15 were safety trials. Forty-one were atmospheric tests (37 at Mururoa Atoll and 4 at Fangataufa Atoll, between July 1966 and September 1974), and 137 were underground nuclear tests (127 at Mururoa Atoll and 10 at Fangataufa Atoll, between June 1975 and January 1996). Of the 15 safety trials, all of which were carried out at Mururoa Atoll, 5 were atmospheric and 10 were underground safety trials [I12].

278. The atmospheric nuclear tests were mostly carried out at a detonation altitude that was sufficient for the fireball not to reach sea level, thereby minimizing the production of local fallout. There were, however, four atmospheric nuclear tests (three at Mururoa Atoll and one at Fangataufa Atoll) in which the devices were mounted on barges floating in the lagoon. Most of the residual radioactive material presently in the accessible environment of the atolls was produced by these nuclear tests. Five atmospheric safety trials were conducted on the northern part of Mururoa Atoll.

279. The underground nuclear tests were conducted in the basalt basement at depths of between about 500 and 1,100 m in shafts drilled vertically beneath the rims of the lagoons. Much of the residual radioactive material associated with the underground nuclear tests was trapped in molten basalt rock that solidified as glass-like lava, but some radionuclides were deposited on fractured basalt rock that collapsed into the cavity-chimney and remained available for exchange with water in the cavity-chimney. The ten underground safety trials were carried out in shafts drilled vertically beneath the rim on the north-eastern part of Mururoa Atoll. The three underground safety trials that involved some fission energy release took place in carbonate formations at depths in excess of 280 m [I12].

280. The closest inhabited atoll was Tureia (population 140) at a distance of 120 km to the north; only 5,000 persons lived within 1,000 km of the test site. A larger population (184,000 in 1974) was located 1,200 km to the north-east, at Tahiti. Under the conditions that normally prevail at the test site, radioactive debris of the local and tropospheric fallout was carried to the east over uninhabited regions of the Pacific. On one occasion, however, material was transferred to the central South Pacific by westerly moving eddies within a few days of the tests. French scientists have identified five tests where regional population groups were more directly exposed. A single rainout event caused exposures in Tahiti after the test of 17 July 1974. Exposures resulted mainly from external irradiation from deposited radionuclides. Milk production on Tahiti is sufficient for only ~20% of local needs, and consumption is low in any case, which limited ingestion exposures. Estimated effective doses to maximally exposed individuals from the five events combined were in the range 1–5 mSv in the year following the test. A collective effective dose of 70 man Sv was estimated for all local exposures at this test site [U3].

281. *Lop Nor test site (Chinese test site).* The Chinese nuclear weapons testing programme was carried out at the Lop Nor test site in western China; 22 atmospheric tests and 12 underground tests were conducted between 1964 and 1988 [S22, U3]. Limited information is available in the literature on local deposition following the tests. External exposures in cities or towns within 400–800 km downwind of the test site are estimated to average about 0.044 mSv, assuming 80% indoor occupancy and a building shielding factor of 0.8 [S22].

282. The adult thyroid dose estimates range from 0.06 mGy in Taiyuan to 2.5 mGy in Lanzhou. Thyroid doses of infants would have been about 10 times higher. The average thyroid dose received by the Chinese population as a result of the tests conducted at Lop Nor was estimated to be about 0.14 mGy. Even though the average deposition density of ^{90}Sr seems to have been lower in China than in the rest of the northern hemisphere, internal doses from ^{90}Sr are estimated to be higher in China as a consequence of the diet of the Chinese population. The average effective dose resulting from intake of ^{90}Sr was estimated to be 0.27 mSv, most of this due to tests not conducted on Chinese soil.

(b) Underground tests

283. There have been 1,877 underground nuclear tests. Some gaseous radionuclides were unintentionally vented during a few underground tests, but available data are insufficient to allow an accurate assessment of the radiological impact. The total explosive yield of the underground tests is estimated to be 90 Mt, much smaller than for the earlier atmospheric tests. The yields for the tests performed by India, Pakistan and the Democratic People's Republic of Korea (DPRK) are not included in this total. Although most of the debris remains underground, it is a potential long-term source of human exposure. The total number of tests performed by each country is shown in figure XXIX.

284. The most recent test prior to the Committee's report was performed by the DPRK, on 9 October 2006. Between 21 and 25 October 2006, elevated levels of atmospheric ^{133}Xe were observed in Yellowknife, Canada. The measurements could not be traced back to known nuclear facilities, and applying atmospheric modelling to backtrack the dispersion shows that the amount measured is consistent (to within an order of magnitude) with simple leak scenarios assumed for a low-yield underground nuclear explosion on the Korean peninsula [S3].

(c) Nuclear weapons production

285. In addition to actual weapons tests, the installations where nuclear material was produced and weapons fabricated were another source of radionuclide releases to which local and regional populations were exposed. Some information on this practice was presented in the UNSCEAR 1993 Report [U6]. Especially in the earliest years of weapons production, pressures to meet production schedules and the lack of stringent waste discharge controls resulted in higher local exposures than in later years. Also, at some sites, weapons are now being dismantled.

(i) United States

286. Nuclear weapons plants in the United States included: Fernald, Ohio (materials processing); Portsmouth, Ohio, and Paducah, Kentucky (enrichment); Oak Ridge, Tennessee (enrichment, separation, manufacture of weapon parts, laboratories); Los Alamos, New Mexico (plutonium processing, weapons assembly); Rocky Flats, Colorado (manufacture of weapons parts); Hanford, Washington (plutonium production); and Savannah River, South Carolina (plutonium production). There are many more sites at which such operations were conducted and where wastes were stored or disposed of. Estimates of historical releases of radioactive material during different periods of operation of the nuclear installations have been reviewed in reference [U3].

(ii) Former Soviet Union

287. There are three main sites where weapons materials were produced in the former Soviet Union: Chelyabinsk, Krasnoyarsk and Tomsk. Relatively large routine releases occurred during the early years of operation of these facilities. In addition, accidents contributed to background levels of contamination and to the radiation exposure of individuals living in the local and regional areas.

288. *Chelyabinsk.* The Mayak nuclear material production complex is located in the Chelyabinsk region between the towns of Kyshtym and Kasli near the eastern shore of Lake Irtyash. Uranium–graphite reactors for plutonium production and a reprocessing plant began operating in 1948. Relatively large discharges of radioactive material into the Techa River occurred between 1949 and 1956. The available information on exposures to the local population was summarized in the UNSCEAR 1993 Report [U6]. The individuals most highly exposed as a result of the releases into the Techa River were residents of villages along the river, who used the river for drinking water, fishing, waterfowl breeding, watering livestock, irrigation of gardens, bathing and washing. In April–May 1951, a heavy flood resulted in contamination of the flood plain used for livestock grazing and hay making. The collective dose to the most exposed population from 1949 to 1956 was 6,200 man Sv, with an average individual effective dose of about 300 mSv, ranging from 36 to 1,400 mSv [A7]. Doses due to external irradiation decreased in 1956, when residents of the upper reaches of the river were moved to new locations and the most highly contaminated parts of the flood plain were enclosed. For some inhabitants, however, the Techa River contamination remains a significant source of exposure to the present day.

289. *Krasnoyarsk.* The Krasnoyarsk nuclear material production complex is located about 40 km from the city of Krasnoyarsk. The radiochemical plant for irradiated fuel reprocessing began operation in 1964. In 1985, a storage facility was put into service for spent fuel assemblies from reactors in the Soviet republics of Russia and Ukraine. There are plans to reprocess fuel from the civilian nuclear fuel cycle at the Krasnoyarsk site in the future.

290. Radioactive waste discharges from the Krasnoyarsk complex enter the Yenisei River. Trace contamination can be found along the river from the complex to the estuary, about 2,000 km away. An estimate for the collective dose resulting from radioactive discharges from the Krasnoyarsk complex during 1958–1991 was about 1,200 man Sv [U3]. The most important contributor (70%) to this dose was fish consumption. External exposure due to the contaminated flood plain accounted for 17% of the collective dose. The main radionuclides contributing to the internal dose due to fish consumption were ^{32}P, ^{24}Na, ^{54}Mn and ^{65}Zn. The main contributors to the external dose (over 90%) were gamma-emitting radionuclides, primarily ^{137}Cs, ^{60}Co and ^{152}Eu. Individual doses varied over a wide range, from 0.05 to 2.3 mSv/a. The major portion of the collective dose (about 84%) was received by populations living within 350 km of the site of the radioactive discharges.

291. In 1992, the direct-flow reactors of the Krasnoyarsk complex were shut down. This reduced considerably the amount of radioactive discharges to the Yenisei River, and the annual collective dose to the population was decreased by a factor of more than 4. Estimates of average annual doses for the period 1993–1996 were 30 μSv for external doses and 20 μSv for internal doses. With a local population of 200,000, the annual collective effective dose is estimated to be 10 man Sv.

292. *Tomsk.* The Siberian nuclear material production complex is located in the town of Tomsk-7, on the right bank of the Tom River 15 km north of the city of Tomsk. The Siberian complex was commissioned in 1953. Radionuclides in liquid waste are discharged into the Tom River, which flows into the Ob River. An estimate for the collective dose due to radioactive discharges from the Siberian complex between 1958 and 1996 is 1,200 man Sv [U3]. During the period 1990–1992, three of the five reactors of the Siberian Complex were shut down, reducing considerably the amount of radioactive discharges to the Tom River and the annual collective dose to the population. The collective effective dose was estimated to be 200 man Sv. The largest contributor (73%) to this dose was from fish consumption. The main radionuclides contributing to the internal dose due to fish

consumption were ^{32}P and ^{24}Na. About 80% of the collective dose was received by the populations living within 30 km of the site of the radioactive discharges [U3].

(iii) United Kingdom

293. The production of nuclear material and the fabrication of weapons began in the 1950s in the United Kingdom. The work was continued for several years at sites such as Springfields (uranium processing and fuel fabrication), Capenhurst (enrichment), Sellafield (plutonium production reactors and reprocessing), Aldermaston (weapons research) and Harwell (research). Subsequently, work related to the commercial nuclear power programme was incorporated at some of these sites. In the earliest years of operation of these installations, radionuclide discharges were associated almost wholly with the military fuel cycle.

294. Plutonium production reactors were operated in the United Kingdom at Sellafield (two graphite-moderated, gas-cooled reactors known as the Windscale Piles) and later at Calder Hall on the Sellafield site and at Chapelcross in Scotland.

(iv) France

295. A nuclear programme in France began in 1945 with the creation of the Commissariat à l'énergie atomique. The nuclear research laboratory at Fontenay-aux-Roses began activities the following year. The first experimental reactor went critical in 1948 and a pilot reprocessing plant began operation in 1954. A second experimental reactor was constructed at the Saclay centre. From 1956 to 1959, three larger production reactors began operation at the Marcoule complex on the Rhône River. These gas-cooled, graphite-moderated reactors operated until 1968, 1980 and 1984, respectively. A full-scale reprocessing plant was built and operated from 1958, also at the Marcoule site. Two more plants to reprocess fuel from commercial reactors were constructed at La Hague in the north of France, being completed in 1966 and 1990. The systematic reporting of radionuclide discharge data may also reflect the reprocessing of commercial reactor fuel.

(v) China

296. The Institute of Atomic Energy was created in 1950. The first experimental reactor was constructed in Beijing, and a uranium enrichment plant was built at Lanzhou in Ganzu Province in western China. A nuclear weapons development programme was initiated in China that led to the first nuclear explosion by that country in 1964. The first nuclear test was of an enriched uranium device. Plutonium production and reprocessing were conducted at the Jiuquan complex, also located in Ganzu Province. The production reactor began operation in 1967 and the reprocessing plant in 1968. Production and reprocessing also occurred in Guangyuan in Sichuan Province, where larger installations were constructed. Weapons were assembled at the Jiuquan complex. Assessments of exposures due to nuclear weapons production in China have been reported and doses to populations surrounding specific installations have been estimated [U3]. This experience relates to the military fuel cycle, since China's commercial nuclear power programme started only in the 1990s.

2. Residues in the environment

(a) Nuclear test sites

297. As described earlier, radioactive debris from an atmospheric nuclear weapons test is partitioned between the local ground or water surface and the tropospheric and stratospheric regions, depending on the type of test, the location and the yield. The subsequent precipitation or depositing of the debris is termed "local fallout" when it is locally dispersed, and "tropospheric fallout" and "stratospheric fallout" when globally dispersed.

298. Exposures due to global fallout were described earlier in this annex. Local fallout can constitute as much as 50% of the production for surface tests, and includes large radioactive aerosol particles deposited within about 100 km of the test site. In some tests, the contributions to total fallout exposure of doses to people close to the sites have been substantial, and these sites must be considered actual or potential sources of public exposure. This subsection focuses on recent efforts towards estimating potential exposures associated with present and future occupation of former nuclear test sites.

(i) Maralinga and Emu

299. As a result of the nuclear weapons tests, residual radioactive contamination in the Maralinga and Emu areas covers some hundreds of square kilometres. The possible exposures associated with present and future occupation of these areas would be mainly of local aboriginal populations, who are likely to constitute the majority of future inhabitants of the areas. The migratory lifestyle of the aboriginal people in the areas makes an assessment of population doses uncertain, and only best estimates for doses to individuals will be discussed here. The assessment has been limited to consideration of the consequences of existing surface contamination. The consequences of the removal of activity from the burial pits known to exist in the areas have not been considered [H7].

300. The possible exposure pathways foreseen are:

- Inhalation of material resuspended from the ground, including both natural wind-driven resuspension and resuspension arising from mechanical disturbance of both soil and fire ash;

- Ingestion of foodstuffs and associated soil (contamination of foodstuffs with soil and fire ash) and water ingestion; special consideration of deliberate soil ingestion (a practice called "pica") is also discussed;
- Contamination of sores and wounds;
- External gamma irradiation due to radioactive material on the ground;
- Beta irradiation due to radioactive material on the ground and on skin and clothing.

301. A further potential exposure pathway, the handling of contaminated objects and fragments, has not been included in this assessment. Measurements have been made of these contaminated items, and doses resulting from prolonged proximity to or handling of such items may be considerable. There is, however, no information on the likelihood and duration of such exposures, and for this reason an assessment of dose has not been attempted.

302. Doses are calculated to the aboriginal population having a semi-traditional lifestyle. It may be assumed that doses to other groups will be lower, with the exception of persons carrying out particular activities such as souvenir hunting for contaminated fragments. There is also considerable difficulty in estimating individual doses realistically because of the great variability in the radionuclide levels in different areas. In areas contaminated by the atomic explosions (the "major trials"), the significant radionuclides currently are neutron activation products, principally ^{60}Co and ^{152}Eu, and fallout radionuclides, principally ^{90}Sr, and ^{155}Eu. More significant radionuclide levels remain as a result of the various chemically triggered explosions (the "minor trials").

303. The dose assessment for different contaminated zones, identifying the critical groups and the most relevant radionuclides, is shown in table 37. The calculated doses assume 100% residence in the area over the period of a year and that caught food is obtained and cooked locally (for kangaroo, a representative and site-independent average concentration for the meat was used). There is therefore a degree of conservatism incorporated into the calculations, which is substantial for the smaller zones. A considerable range of annual effective dose estimates exists, from 0.5 mSv in the area of Emu–Totem I (at the limit of aerial detection of ^{137}Cs) to 500 mSv at Inner Taranaki. As expected, the highest doses would be incurred from occupancy in the regions immediately surrounding the test sites. Continuous occupancy in such areas is very unlikely because of their small size. Considerably lower but still significant doses would be incurred at the outermost contour lines defined by aerial survey.

(ii) Mururoa and Fangataufa

304. The aim of recent assessments of the situation at the Mururoa and Fangataufa Atolls was to estimate the radiation doses that people anywhere in the South Pacific would receive due to the residual radioactive material already present in the accessible environment of Mururoa and Fangataufa and their surrounding waters. The main scenario addressed was the release of residual radioactive material currently underground at the atolls into the lagoons or directly into the surrounding ocean as a result of the normal migration of the residual radioactive material through the geosphere, modified by the hydrogeological effects of the nuclear testing. Particular attention was paid to three radionuclides of potential radiological significance—^{239}Pu, ^{137}Cs and ^{90}Sr—and additionally to ^{3}H, which was a useful tracer for validating models.

305. There are no records of previous permanent indigenous habitation of the Mururoa and Fangataufa Atolls, although some intermittent habitation of Mururoa Atoll has occurred. The study postulated hypothetical dwellers on the atolls eating largely local seafood and locally grown produce, and estimated the upper bound of doses that might be incurred if the atolls were actually to be inhabited. It also provided a conservative estimate of the doses being received by the present population of Tureia Atoll, the nearest inhabited land (about 130 km from the Mururoa and Fangataufa Atolls).

306. The most important contributors to the overall radionuclide release rates were the 12 nuclear tests carried out at Mururoa Atoll early in the nuclear test programme. In terms of activity, tritium dominated the early releases, but with activity concentrations that were of no radiological significance. Since the tests, other radionuclides, including ^{137}Cs and ^{90}Sr, have been effectively retained underground within the basalt basement, most of their activity decaying and only small amounts being released. Plutonium continued to be released over long periods of time but at very low rates. The modelling predicted that concentrations of ^{137}Cs and $^{239+240}$Pu in the lagoon water would be unlikely to exceed present levels at any time in the future. Concentrations of ^{90}Sr and ^{3}H could rise marginally above current levels, but only during the next few decades. The dispersion of residual radioactive material throughout the ocean will lead to long-term concentrations of some radionuclides, which will decrease to background oceanic levels beyond about 100 km from the atolls. Thus at Tureia Atoll the predicted concentrations will be around background levels [I12].

(iii) Bikini

307. In 1997, the official journal of the Health Physics Society, *Health Physics*, devoted a complete issue [H16] to the consequences of nuclear weapons testing in the Marshall Islands. The information presented in this section is mainly related to the prevailing radiological circumstances and their implications for the future habitability of Bikini Atoll. Currently the significant residual radionuclides from nuclear tests that remain in the soil and the surroundings of the atoll are ^{137}Cs, ^{90}Sr, $^{239+240}$Pu and ^{241}Am. These are found to varying degrees in both terrestrial and marine environments. The

unique composition of coral soil, which is primarily calcium carbonate with no clay, produces a pattern of availability to plants of ^{137}Cs and ^{90}Sr very different from that for which most data (which relate to aluminium silicate clay soils of the Americas and Europe) are reported in the literature [R17].

308. Bikini Island, the primary island for habitation at Bikini Atoll, has the highest concentrations of ^{137}Cs per unit mass of soil and vegetation in the atoll. The average ^{137}Cs concentration varies over a considerable range among the atoll's islands. The average ^{137}Cs concentration in soil and vegetation on Eneu Island, the other main island of residence, is about 10–13% of that on Bikini Island. The ^{137}Cs concentrations in soil on Nam Island and Enidrik Island (the two other islands large enough for possible residence) are about 70% and 15%, respectively, of that on Bikini Island.

309. Concentrations of transuranic radionuclides ($^{239+240}$Pu and ^{241}Am), and their ratios to concentrations of ^{137}Cs and ^{90}Sr, vary around the atoll, reflecting differences in the design of the nuclear devices detonated near the various islands. In general, radionuclide concentrations decrease rapidly with depth in the soil column, although there are exceptions in parts of some islands. The activities of radionuclides per unit dry weight of soil on Bikini Island are shown in table 38. The concentration of ^{137}Cs in coconut reaches values up to 6,000 Bq/kg. Some other fruits, such as pandanus and breadfruit, have average ^{137}Cs concentrations of about 4 and 400 Bq/kg, respectively. The ^{90}Sr activities are less than 10% of the respective ^{137}Cs activities in the relevant foodstuffs. The activities of $^{239+240}$Pu and ^{241}Am are even lower than the ^{90}Sr activities [R17]. The results from resuspension studies show that the average resuspension of surface soil is very low, with resuspension factors ranging from 10^{-10} to 10^{-11} m^{-1}. On the basis of the measured activity concentrations in soil, the concentrations of $^{239+240}$Pu and ^{241}Am in air are expected to be very low, and consequently the expected contribution to doses due to radiation exposure via inhalation pathways is judged to be insignificant.

310. The residual radionuclides, ^{137}Cs, ^{90}Sr, $^{239+240}$Pu and ^{241}Am, are present in the atoll's lagoon, mainly in sediments but also in water and biota. Caesium-137 is found in very low concentrations in lagoon sediment, water and fish. Caesium compounds are generally highly soluble, and the major part of the original inventory of ^{137}Cs in the lagoon has long since dissolved and become mixed into the world's oceans. Strontium-90, which is chemically similar to calcium (a major component of the coral soils as calcium carbonate), competes with the very large quantities of calcium available for uptake by and distribution in marine species. It is also chemically bound in the growing coral and coral sediment, and remains in the lagoon environment primarily in the carbonate matrix. Consequently, ^{90}Sr is relatively unavailable to marine life.

311. The best estimate for the total inventory of $^{239+240}$Pu and ^{241}Am in Bikini Atoll sediments is 103 ± 25 TBq and 93 ± 10 TBq, respectively. On Bikini Island the absorbed dose rate in air measured at 1 m above the ground varied from about 0.01 to 5 mGy/a in studies conducted in August 1978. The values decay-corrected to 1999 would be about 60% of the 1978 values, i.e. from 0.006 to 3 mGy/a. Other potential routes by which exposure could occur (such as swimming or diving in the lagoon) have been analysed. The contributions to dose via these pathways were found to be so small that they could be neglected in the general dose assessment.

312. Assessments performed to evaluate the potential committed doses to the population that might in future live on Bikini Island have estimated the average annual effective dose due to external gamma radiation, based on typical local occupancy habits and decay-corrected to 1999, as 0.4 mSv. The overall annual individual dose was predicted to be about 8.0 mSv for a low-calorie diet. For a high-calorie diet assumed to consist of both imported and locally derived foods, a value of 4.0 mSv was estimated, and for a diet consisting of only locally derived foodstuffs, the overall annual dose was estimated as 15 mSv. In practice, doses resulting from a diet of locally derived foodstuffs are unlikely to be incurred under the current conditions, as the present Marshallese diet contains (and would in the near future presumably continue to contain) a substantial proportion of imported food, which is assumed to be free of residual radionuclides. The uptake of ^{137}Cs into terrestrial foodstuffs accounted for the largest fraction of the total estimated dose (table 39) [B34].

313. Transuranic radionuclides in the lagoon remain an important potential source of radiation. There is evidence that plutonium is indeed transferred from sediments into the aquatic ecosystem in small but measurable concentrations through the action of biogeochemical processes. However, the observed transfer of these radionuclides through the marine food chain to human foodstuffs is very low. The available information further indicates that actions of severe storms and hurricanes in the area over the past 40 years do not appear to have mobilized or transported the transuranic radionuclides to any significant extent [I9].

(iv) Semipalatinsk, Kazakhstan

314. Emphasis in this assessment is given to residual radioactivity from nuclear testing. As such, the main tests of interest are those that resulted in local fallout. These include the surface tests, excavation experiments and three underground tests in which an unplanned venting of radioactive material to the atmosphere occurred. In most areas outside the nuclear test site, external radiation dose rates and activity concentrations in soil are similar to typical levels in other regions and countries where no nuclear weapons testing has been carried out. The estimated annual effective dose to persons outside the nuclear test site due to residual radionuclides is 0.1 mSv at most. Actual exposures are more likely to be of the order of a few microsieverts per year, a dose rate very close to the global average due to fallout [I10].

315. Over most of the test site there is little or no residual radioactivity. However, the Ground Zero and the Lake Balapan areas are exceptions and are heavily contaminated. The only on-site inhabitants during the testing programme were in the town of Kurchatov and in the small settlements of Akzhar and Moldari along the northern edge of the site. Recently there has been limited resettlement within the area, mostly by semi-nomadic farmers and herders. There is some evidence that they have grazed animals in both the Ground Zero and the Lake Balapan areas. It is not known if there are any settlements close to the other cratering test sites.

316. Activity concentrations in soil are available for the most radiologically important radionuclides at most occupied locations off-site, but for few locations on site. Outside the nuclear test site, the results of ^{137}Cs measurements from IAEA missions in 1993 and 1994 all fell within the range 5–100 Bq/kg. Most results were at the lower end of this range, which is typical of global average fallout levels. Results for plutonium in soil fell within the range 0.2–7 Bq/kg, measured in 1991 and 1992. (For perspective, concentrations of ^{239}Pu in surface soil in south-central England as a result of weapons fallout are in the range 0.5–1.7 Bq/kg.) An exception to this is in the village of Dolon, where much higher plutonium levels (by a factor of up to 100) have been recorded.

317. The absorbed dose rates due to terrestrial sources outside the nuclear test site have been extensively measured and are shown in table 40. Taken together, the values represent the results of a survey conducted between 1991 and 1994 of approximately 600 locations around the entire nuclear test site perimeter. All nearby centres of population are believed to have been included. The values measured outside the test site are almost entirely within the range of dose rates due to natural sources measured in different countries and reported by UNSCEAR (0.024–0.160 μGy/h).

318. Measurements of activity from inside the nuclear test site are scarce in comparison with the data available for outside. The gamma spectrometry aerial survey undertaken in 1990 indicated that the absorbed dose rate over the entire test site was within the range 0.07–1 μGy/h. Measurements made at Ground Zero with survey meters indicated that the dose rate changed rapidly with increasing distance from the epicentre, such that values close to normal background levels were indicated at distances of a few hundred metres. Similar variations were observed in and around the Lake Balapan crater. High levels of actinides and fission products are present close to Ground Zero and Lake Balapan.

319. Low concentrations of artificial radionuclides in soil from the vicinity of the main settlements suggest, however, that the local food chain is unlikely to be a significant pathway of exposure. A limited food-sampling programme supports this [I10]. Drinking water samples taken from local wells outside the test site and one inside the test site indicated that ^{137}Cs and ^{90}Sr concentrations were not significant. The possible future contamination of groundwater owing to the leaching of radionuclides from underground tests must be considered, however. Air sampling carried out during 1991–1992 inside and around the test site by the former Soviet Union indicated negligible airborne levels of ^{137}Cs and $^{239+240}$Pu in Dolon and other villages.

320. External radiation exposure has been assessed from measurements of absorbed dose rates. Internal radiation exposure from inhalation has been assessed on the basis of activity concentrations in soil and assumptions regarding the levels of resuspended dust. The ingestion pathway has been modelled using environmental transfer factors (representing transfer from soil to the food chain) and a typical local diet. The ingestion of soil has also been assessed. The estimated doses to adults, assuming continuous habitation of the area, are given in table 41. The exposure of children has also been estimated, and in all cases the total annual doses are lower than those for adults. The annual dose estimated to persons living in settlements outside the test site is 0.06 mSv, with a higher value of 0.14 mSv for Dolon. Because of the conservative assumptions made in the assessment, these values are likely to be overestimates; a more realistic estimate of the dose to an average person living in the settlements is likely to be about one tenth of these estimates.

321. Two exposure scenarios were considered for the nuclear test site. The first assumes a group of visitors that stay at the highly contaminated areas for one hour per day and keep animals that take 10% of their feed from these areas. The values in table 41 indicate the level of dose that a small number of frequent visitors might receive. The external exposure pathway dominated the doses to visitors to these areas. The second scenario considered potential future settlement. The most pessimistic future scenario is one in which persons permanently inhabited the Ground Zero or Lake Balapan areas and derived all their crops and animal products from within these areas. The estimated potential future doses to permanent inhabitants are also given in table 41. External exposure would be the main exposure pathway for persons who might in the future permanently inhabit these two areas, but ingestion would also make a significant contribution, owing to the production of food in the contaminated areas. The estimated annual doses to permanent residents due to residual radioactivity on the site are about 140 mSv [I10].

322. Recent surveys at the Semipalatinsk test site highlighted the high degree of variability in the radiostrontium contamination. The highest values measured were associated with leakage from tunnels in the Degelen area, where 239 underground tests were performed, including one as part of the programme on peaceful nuclear explosions. It was also suggested that some ^{90}Sr may be in a highly mobile form and that ^{90}Sr ingestion is a comparatively important pathway of exposure compared with other radionuclide exposures at the test site and in the surrounding areas [H25].

(v) Novaya Zemlya, Russian Federation

323. Current dose rates in the Novaya Zemlya islands generally vary from 0.08 to 0.12 μGy/h, which is similar to the range observed in adjacent areas not used for testing and which essentially corresponds to natural background levels, although in small areas much higher dose rates can be detected. The internal dose rate due to ^{137}Cs (and to a lesser extent due to ^{90}Sr) for reindeer herders is estimated to have been about 1 mSv/a since the early 1960s; dose rates to urban residents were estimated to have been about 100 times lower [S22].

(vi) Nevada, United States

324. Four areas in Nevada have been used under the United States nuclear test programme: the NTS, the Tonopah Test Range, Project Shoal and the Central Nevada Test Area. The NTS encompasses 3,496 km^2 of land under the jurisdiction of the United States Department of Energy (USDOE). The Tonopah Test Range was withdrawn from public use for military use in the 1940s. Since 1956, the Tonopah Test Range has been managed by the USDOE and encompasses 1,606 km^2 of land used for defence and related research, design and testing activities. The Project Shoal Area was withdrawn from public use for purposes of underground nuclear testing. The Project Shoal underground nuclear test took place on 1963. The area is currently used by the United States Navy for testing and training for tactical manoeuvring and air support. Subsequent to an underground test in 1968, the withdrawal of public lands for the Central Nevada Test Area has remained unchanged and the area remains under the control of the USDOE. Cattle grazing and recreation are the main uses of the area around this site.

325. Radioactive waste management and disposal operations began at the NTS in the early 1960s, and low-level, transuranic mixed and classified low-level wastes have been disposed of in selected pits, trenches, landfills and boreholes on the NTS. The NTS currently serves as a disposal site for low-level waste generated by USDOE-approved operators and also as a storage site for a limited amount of transuranic mixed waste. The topography of the NTS has been altered by historic USDOE actions, particularly underground nuclear testing. The principal effect of testing has been the creation of numerous craters in Yucca Flat and on Pahute and Rainier Mesas. Underground nuclear testing has resulted in impacts on the physical environment in terms of ground motion, disruption of the geological media, surface subsidence, and contamination of the subsurface geological media and superficial soils. Waste disposal operations have also resulted in surface disturbance and the placement of material having long-term impacts on the environment. Table 42 summarizes the baseline information on the residual radionuclide inventory at the NTS.

326. Most of the areas considered in the NTS are located within the Great Basin, an area from which no surface water leaves except by evaporation. Streams in the area are ephemeral. Although precipitation is very low in the region, during extreme precipitation events there is some risk of flooding along arroyos and around playa lakes. Throughout the region, springs are the only natural sources of perennial surface water, but they are not used for human consumption. A considerable volume of groundwater, estimated at 2.7×10^9 m^3, is held in recoverable storage beneath the NTS and the surrounding region.

327. Radioactive contamination of surface areas at the NTS resulted primarily from the atmospheric testing of nuclear weapons between 1951 and 1962. Additionally, safety tests conducted at the surface between 1954 and 1963 resulted in radioactive contamination of the soil. More than 200 areas that are controlled because of radioactive contamination have been identified and mapped on the NTS.

328. More than 800 underground nuclear tests have been conducted at the NTS. Underground testing has resulted in unavoidable adverse impacts to portions of the land and the geological and groundwater resources, making them unusable for most purposes. Pockets of radioactive contamination surround each underground test location. From data on the number and dates of the underground tests at the NTS, the total activity of radionuclides remaining underground is estimated to be 1.1×10^{19} Bq. Much of this radioactive material remains captured in the original cavity and thus is not available to leach into the groundwater. The impacts of conducting subcritical experiments underground would be much less than those of nuclear testing, since no self-sustaining fission chain reactions occur and much less radioactive material is deposited in the geological environment. As in the case of nuclear testing, the radioactive material is captured underground.

329. Underground nuclear testing has resulted in the contamination of groundwater in the immediate vicinity of a number of tests. The quality of the groundwater has been impaired, but only in these limited areas. No radioactive contamination attributable to USDOE activities has been detected in monitoring wells outside the NTS. Detection of significant contamination is limited to underground testing areas on the NTS. Tritium-contaminated groundwater exists in the subsurface as a result of past underground testing of nuclear weapons performed within the NTS and at two off-site locations, the Project Shoal Area and the Central Nevada Test Area. On the basis of the combined results of studies performed by various authors, the estimated range of peak tritium concentrations at the area of uncontrolled use closest to the NTS varies from 0.02 Bq/L at 150 years after the beginning of migration to 1.4×10^5 Bq/L in 25–94 years. The migration of tritium-contaminated groundwater from the test location at the Project Shoal Area could result in peak concentrations ranging from 1×10^4 to 2.7×10^7 Bq/L at the boundary of the controlled area between 71 and 206 years after the test. No public water well currently exists at this location.

330. The environmental impacts related to the waste management programme are minor compared with those of the other programmes. Underground nuclear detonations create underground cavities into which the soil and rock above the cavity then collapse. The final result is a crater on the surface. Low-level waste at the Area 3 Radioactive Waste Management Site is disposed of in subsidence craters formed from past underground nuclear tests. Waste management programme operations in Area 5 are more diverse and include facilities for hazardous and mixed-waste management in addition to low-level-waste management facilities. After 30 years of waste disposal operations, the USDOE has not detected any contamination in groundwater monitoring wells recently completed near this area.

(vii) Reganne and In Ecker, Algeria

331. Though the Reganne site is at present not sealed off, access to the area of the test sites has been and continues to be restricted by military control. There are practically no roads leading to the Algerian test sites, making access very difficult. A survey has recently been performed at the nuclear test sites [I32]. External dose rate measurements were made at 76 locations. A total of 25 environmental samples were collected. While the number of dose rate measurements was considered adequate, the number of samples collected and analysed was somewhat small, in view of the size of the areas. Most of the areas at the test sites have little residual radioactive material except: *(a)* the ground zero locations of the Gerboise Blanche and Gerboise Bleue atmospheric tests at the Reganne test site, where the areas that have elevated external dose rates are only a very small part of the tracts surveyed and are confined to distances of a few hundred metres from the four individual ground zero points; and *(b)* at Taourirt Tan Afella in the vicinity of the E2 tunnel, where at the opening of one of the partially confined underground tests an accidental release of fission products mixed with molten rock took place and formed a large bed of hardened lava.

332. Despite the preliminary nature of the sampling and investigation programme, all conclusions indicate that present-day exposure rates do not justify a requirement for intervention, in view of the current state of development of the region. However, if the economic conditions change in the area, the requirement for intervention at the Gerboise Bleue, Gerboise Blanche and E2 tunnel sites should be reconsidered. At Reganne, for occasional visitors to the site, exposures to external radiation due to residual radionuclides from the tests are likely to be low, i.e. less than a few microsieverts per day, while the area at Taourirt Tan Afella has been protected from public intrusion by a security fence.

333. In addition to the above-mentioned sites, at the Adrar Tikertine experimental site, at In Ecker, plutonium in fine particulate form was spread over a wide area. The concentration of plutonium in sand was determined from a small number of samples that were not sufficient to be representative of the area and which therefore could not be used for a detailed or precise evaluation of the inventory or specific distribution of activity in the Adrar Tikertine area. Nevertheless, the activity concentration of anthropogenic radionuclides in those samples was generally below laboratory detection limits. Thus it is expected that the residual surface contamination from the plutonium dispersion experiments is unlikely to give rise to doses to nomadic herders or their families exceeding 1 mSv/a [I32].

(viii) Lop Nor, China

334. Lop Nor, located in central Asia in a vast desert region in western China, was the location for 34 nuclear weapons tests conducted between 1964 and 1988; of these, 22 were atmospheric tests and 12 were underground. Little information is publicly available on doses received by the public or by test personnel in China. It is known, however, that the trajectory of the cloud carrying radioactive debris was determined for each test. The Ministry of Public Health set up a nationwide monitoring network for environmental radioactivity in the early 1960s, but the Lop Nor test site has never been opened to Western scientists and no information could be located on present levels of contamination and public exposure, although available information indicates that the site was made a reserve for the highly endangered Bactrian camel [S22].

(ix) Amchitka, United States

335. Following a report stating that there was radioactive leakage from the test site to terrestrial and freshwater environments, recent surveys determined tritium concentrations in surface water in the range 0.41–0.74 Bq/L at the sites sampled, which included the reported leakage sites. Only at the Long Shot test site, where leakage of radioactive gases to the near surface occurred in 1965, were higher ^{3}H levels (5.8 Bq/L) still observed in 1997. The mean $^{240}Pu/^{239}Pu$ value for all of the Amchitka samples was 0.1991, with values ranging from 0.1824 to 0.2431.

336. The measured ^{3}H levels and $^{240}Pu/^{239}Pu$ ratios in freshwater moss and sediments at Amchitka provide no evidence of leakage occurring at the sites. Deviations from the mean $^{240}Pu/^{239}Pu$ ratios for global fallout were observed in marine algae, sediment and pooled Amchitka samples, and may suggest another source of plutonium release to the marine environment; however, uncertainties in analyses and environmental processes need to be fully assessed before any firm conclusions can be drawn. These results do not necessarily mean that leakage from the Amchitka underground nuclear tests is not occurring or will not occur into the North Pacific Ocean or the Bering Sea. Hydrogeological modelling predicts that leakage of ^{3}H from the test sites into the marine water might be seen beginning 20 to 3,000 years from now [D2].

(b) Sites contaminated by non-nuclear tests

(i) War sites contaminated with depleted uranium

337. During the enrichment process for natural uranium, the ^{235}U fraction is increased from its natural level (0.72% by mass) to 2% or more. The uranium that remains after the enriched fraction has been removed has reduced concentrations of ^{235}U and ^{234}U. This by-product is known as depleted uranium (DU). The ^{235}U content in DU is depleted to 0.2–0.3%, about one third of its original natural fraction [U17]. Since ^{234}U is a lighter isotope, its concentration is correspondingly higher in fuel uranium and lower in DU compared with natural uranium. The fact that DU has lower concentrations of ^{235}U and ^{234}U than natural uranium also means that DU is less radioactive than natural uranium. Only traces of isotopes beyond ^{234}Th and ^{231}Th in the decay chain are present in DU, as the other decay products have not had time to build up in significant quantities in the time since the DU was originally produced. The total specific activity of natural uranium is 25.4 Bq/mg, while that of DU is 14.2 Bq/mg. Table 43 gives the main physical properties of the three isotopes of uranium and compares their relative abundance by mass and activity in natural uranium and DU [U17].

338. DU has been used for both civilian and military purposes for many years. The civilian applications include uses in radiation shielding or as counterweights in aircraft. DU is also used for heavy tank armour. Armour made of DU is much more resistant to penetration by anti-armour munitions than conventional hard rolled steel armour plate. Also, owing to its high density, its high melting point and its property of becoming "sharper" as it penetrates armour plating, DU is used in anti-tank munitions. DU is pyrophoric; on impact against its target, a DU penetrator will ignite, breaking up into fragments and forming an aerosol of particles ("DU dust") that can ignite spontaneously in air [I24].

339. Both tanks and aircraft can fire DU munitions, with tanks firing larger-calibre rounds (105 and 120 mm) and aircraft firing smaller-calibre rounds (25 and 30 mm). Typically the DU round fired by A-10 aircraft has a conical DU penetrator, 95 mm in length and with a diameter at the base of 16 mm, fixed inside an aluminium jacket. The weight of one penetrator is approximately 300 g [U20]. When the penetrator hits an armoured vehicle, the penetrator continues through the armouring while the jacket usually remains outside.

340. A typical burst of fire by an A-10 aircraft occurs for 2–3 s and involves 120 to 195 rounds. These hit the ground in a straight line, 1–3 m apart, depending on the angle of the approach. Penetrators that either hit non-armoured targets or miss targets will generally remain intact and become buried in the ground. The depth depends on the angle of the approach, the speed of the plane, the type of target and the nature of the ground surface. In clay soils, penetrators used by A-10 attack aircraft may reach a depth of more than 2 m. Conversely, penetrators hitting hard objects such as rocks and stones may ricochet and be found lying on the surface some distance from the targeted area [U20].

341. Normally 10–35% (maximum 70%) of the round becomes aerosol on impact with armour. Most of the dust particles are less than 5 μm in diameter and can be dispersed in the environment, spreading according to wind direction. The amount of dust produced is actually small, because the vast majority of DU munitions miss their targets or hit soft targets and remain intact. The dispersion of the DU dust leads to resuspended activity in the air and subsequent deposition on the ground. However, such radioactive material should be limited to within about 100 m of the target. In a combat situation, the main radiological hazard associated with DU munitions is inhalation of the aerosols created when DU munitions hit an armoured target [U20].

342. Small penetrator fragments and DU dust are gradually transported into the upper soil layer by weathering processes. Wind, rainwater or surface water flow may also redistribute the dust. Mobilization of DU through the soil profile and the possible migration of DU into groundwater will depend on a number of factors, such as the chemistry and structure of the surrounding soil, rainfall and hydrology [U20].

343. The alpha particles emitted by DU are very energetic but have a very limited range in tissue. They can barely penetrate the external layer of the skin and hence do not pose a hazard in terms of external irradiation, but internal irradiation is an important consideration. Uranium is not generally transferred effectively through food chains; therefore, in environmental assessments, inhalation is the exposure pathway that usually merits primary attention. Processes such as migration through the soil, deposition of resuspended material on to crops and transfer to groundwater may, however, be of interest in the longer term [I24].

344. The only exposure of concern may arise from external beta radiation to the skin if a penetrator is placed in a pocket or is used as an ornament worn on a neck chain. This could result in quite high localized radiation doses after some weeks of continuous exposure. Although there will not be any radiation skin burns, erythema may occur. The resulting gamma radiation exposure will be insignificant, of the same order of magnitude as natural radiation, at most [U17].

345. Although it has been suggested that DU from munitions remaining in Kosovo or other locations may migrate to groundwater, the uranium concentration arising from this source would be undetectable compared with naturally occurring concentrations in water. Oeh et al. [O3] measured water samples and the urinary excretion of uranium in a region of Kosovo where DU munitions were deployed. More than 1,300 urine samples from peacekeeping personnel and unexposed controls of different genders and ages were analysed. The urine measurements for 113 unexposed subjects had a uranium excretion rate of 13.9 ng/d (geometric standard deviation (GSD) = 2.17). The analysis of 1,228 urine

samples from the peacekeeping personnel resulted in a geometric mean of 12.8 ng/d (GSD = 2.60). No DU could be found in any water samples, and there was no difference between urine samples from persons potentially exposed and controls.

346. Metallic DU reacts chemically in the same way as metallic uranium, which is considered to be a reactive material. Studies carried out on penetrators collected in Kosovo, Serbia and Montenegro showed that ground impact caused numerous fine cracks in penetrators. This favours subsequent corrosion and dissolution [U17]. Corrosion occurs relatively quickly when the penetrator remains in the ground and is surrounded by soil. A penetrator can be completely corroded in the 25–35 years following impact. The corrosion products may in turn dissolve and disperse in water. However, the rate of corrosion depends on the composition of the soil. If the penetrator is lying on the ground surface, the corrosion rate is significantly lower. However, the corroded uranium is loosely attached and easily removable. Consequently, if such a penetrator is picked up, it could easily contaminate the skin and clothing of anyone handling it. Buried penetrators and jackets may inadvertently be brought to the surface in the future through digging as part of soil removal or construction work. The corresponding exposures would then be the same as for penetrators and jackets currently lying on the surface.

347. There have been reports that the DU in munitions contained small amounts of other radionuclides, such as isotopes of americium and plutonium as well as ^{236}U. The presence of these man-made radionuclides indicated that some of the DU had been obtained from uranium that had been irradiated in nuclear reactors and subsequently reprocessed, or resulted from contamination of equipment in the processing plant during the reprocessing of spent nuclear fuel [I24].

348. Doses to members of the public living in areas where they could be exposed to DU munitions are very low [I24]. There are several possible pathways through which populations in these areas may be exposed to radiation emitted by DU munitions. The most significant pathway is inhalation of DU particles that have been resuspended either by the wind or by human activities such as ploughing. Fragments of DU can be brought to the surface during the construction of houses, roads, etc. Lumps of DU lying on the ground surface (either complete penetrators or penetrator fragments) can be picked up by members of the public. Consequently, there is a possibility of people being exposed to external beta and gamma radiation and to internal radiation if dust from corroded DU or DU fragments enter the body. The surface radiation from DU includes beta and gamma radiation from its decay product, ^{234}Th. The external dose due to direct contact with DU fragments has been estimated to be 2.3 mSv/h [F7, I24, U17, U20].

349. As mentioned above, the jacket is the non-DU part of a weapon projectile that encases the DU penetrator. The projectile is designed so that the jacket stops upon impact against a hard surface while the penetrator enters the target. Potential exposures arising from jackets are far lower than from penetrators, because the jackets are made of aluminium rather than DU, of which they have only very low levels [U17].

350. It has been confirmed that DU munitions have been used in several recent military conflicts, including the Gulf War in 1991, the conflicts in Bosnia Herzegovina in 1994 and in Kosovo in 1999. It was probably also used in the 2003 Iraq war. Available estimates of the total munitions used in each conflict are presented in table 44.

351. *Kuwait.* The 1991 Gulf War was the first conflict in which DU munitions were used extensively. The total number of rounds expended in the Gulf War is estimated to be about 860,600, representing a total weight of DU of about 286 t [I24]. Of the 3,700 Iraqi army tanks destroyed during the Gulf War, DU munitions accounted for only around 500.

352. A large number of DU munitions were stockpiled on the United States military base of Camp Doha when a fire broke out on 11 July 1991. After the immediate clean-up operations, approximately 300 DU penetrators (corresponding to a total of 1,500 kg of DU) were found to be missing. The area was fenced and access to it restricted. In 2001, remediation actions were conducted. There was evidence of the presence of DU in environmental samples, but the concentrations of ^{238}U were more than two orders of magnitude lower than the values observed in the soil prior to remediation. A person spending several hours each day working on the site could receive a dose of 7.7 μSv over the course of a year, mainly from inhalation of resuspended material. Individuals using the area for recreational purposes would receive doses of about one sixth of this. Access to the area remains restricted, and actual doses due to DU to people working or spending time nearby would be lower still [U24].

353. At the Military Hospital storage site, adjacent to the area where contaminated tanks had been stored, some DU was present in the top 5 cm soil layer. However, the highest concentrations of ^{238}U observed were only about two to four times the value expected from the natural background levels across Kuwait. A person who worked on this part of the site could receive an annual dose due to DU of about 3.3 μSv, almost entirely via inhalation of resuspended material. Annual doses to members of the public using the area for recreation would be less than 1 μSv. Doses to members of the public making use of nearby facilities would be lower still [U24].

354. The site of Um Al Kwaty is used to store several thousand Iraqi military vehicles destroyed during the war, among them 105 tanks contaminated with DU. It is estimated that the tanks stored at the site have a total of about 1 t of DU associated with them. The site also contains 366 heaps of contaminated soil from Al Doha that contain ash from the fire at Camp Doha, fragments of munitions and other

metallic debris. The debris is estimated to contain about 1.5 t of DU. Access to the site is currently restricted [U24].

355. DU rounds were used in an attack on a convoy of Iraqi vehicles at Al Mutlaa, a major and expanding urban area with a population of about 50,000. Vehicles destroyed in the attack have been removed and the road has been completely resurfaced. None of the samples of either soil or vegetation contained detectable amounts of DU, and the concentrations of ^{238}U in the soil samples were consistent with the values expected generally in soil in Kuwait.

356. The Manageesh oilfields cover a very large area south-west of Kuwait City. During the Gulf War they were subjected to repeated air raids involving DU munitions. The area as a whole is thought still to contain several hundred unexploded landmines and cluster bombs. Access to this area is also restricted.

357. Overall, it cannot be excluded that fragments of DU penetrators or entire munitions might still be found and collected by members of the public at locations in Kuwait where DU munitions were used in the 1991 Gulf War. Prolonged skin contact with these DU residues is the only possible exposure pathway that could result in exposures of radiological significance. As long as access to the areas remains restricted, the likelihood that members of the public could pick up or otherwise come into contact with these residues is low [U24].

358. *Bosnia and Herzegovina.* There are 15 target sites confirmed by the North Atlantic Treaty Organization (NATO) in Bosnia and Herzegovina where DU munitions were used, of which one is inaccessible because of the presence of mines. There are also six NATO target sites in the vicinity of Sarajevo for which the coordinates are still missing. These sites could therefore not be investigated. Three of the 14 sites investigated by the United Nations Environment Programme (UNEP) clearly showed DU contamination, confirming the earlier use of DU ordnance. No DU contamination was found at the other 11 sites investigated. None of these sites showed signs of widespread contamination of the ground surface. Ground surface DU contamination was typically limited to areas within 1–2 m of penetrators and localized points of contamination caused by penetrator impacts. Almost 300 contamination points were identified during the mission, but most of them were only slightly contaminated. Given that several thousand DU rounds were reportedly fired against the target sites investigated, the number found is low. It is possible that the majority of the penetrators are buried deep in the ground [U18].

359. DU could be clearly identified in one of the drinking water samples. A second drinking water sample from a well showed traces of DU contamination, which were detectable only through the use of mass spectrometric measurements. DU was found in lichen samples at the three sites mentioned above. There are no reasons to expect the presence of any DU in food, owing to the low dispersion rate in the ground and the low uptake factor in food. DU contamination in air was found at two sites where DU use had been confirmed. The concentrations were very low, and the resulting radiation doses were minor and insignificant. At distances of over 100 m from contaminated areas, no DU could be detected in the air [U18].

360. *Kosovo.* During the Kosovo conflict in 1999, DU weapons were fired from NATO aircraft; it has been reported that over 30,000 rounds of DU were used. Because of the risks posed by mines and unexploded ordnance, the sites investigated by UNEP in 2000 were limited compared with the total area potentially affected by the use of DU in Kosovo and represented some 12% of all sites attacked using DU munitions during the Kosovo conflict [U20].

361. No significant widespread contamination of ground surfaces or soil was found in Kosovo, although localized points of concentrated contamination close to penetrator impact sites or penetrator holes exist. The levels of DU detected decreased rapidly with distance from impact points, the maximum distance at which levels were still measurable being 10–50 m. When a penetrator or a jacket was found on the surface of the ground, the soil below the penetrator normally had measurable levels of DU. The area of the impact point was normally small, i.e. less than 0.04 m^2, but the relative concentration of DU at such a point could be high. The absolute concentration of DU in soil varied from a few milligrams of DU per kilogram of soil to about 18 g of DU per kilogram of soil, which corresponded to about 6% of the weight of a penetrator.

362. The depth of soil beneath impact points with measurable DU levels was normally in the range 10–20 cm, with the activity concentration decreasing with increasing depth. This vertical distribution probably resulted from the dissolution and dispersion of DU following the initial surface contamination or from the penetrator lying on the surface. However, the amount of DU at the impact points was very low and the corresponding exposures insignificant.

363. The surface of penetrators was probably subject to oxidation, as part of the radioactive material was easily removed from the oxidized surface. However, the amount was very low, about 10^{-5} of the mass of the penetrator, i.e. a few milligrams. As in the case of the penetrators, the soil beneath a jacket had measurable activity to a depth of 15–20 cm. The potential exposure to radiation arising from the jackets is much lower than from the penetrators, because the jackets are not made of DU and are only slightly contaminated [U20].

364. It is probable that many penetrators and jackets remain hidden at some metres depth in the ground. No measurable levels of DU were found in houses, vehicles or other objects. Results on the levels in botanical material were not conclusive except for lichen (and possibly bark). No measurable levels of DU were found in milk samples taken from cows grazing in fields that potentially might have elevated levels of DU [U20].

365. *Serbia and Montenegro.* In Serbia, significant levels of DU were found at localized points in the immediate vicinity of penetrators lying on the ground and around penetrator impact marks/holes. The levels of DU detected decreased rapidly with distance from such points, and beyond a distance of one metre were no longer detectable by field measurements. Laboratory analyses of soil samples, however, enabled activity levels to be traced for several metres further from the points. More detailed laboratory analyses of soil samples revealed widespread low levels of DU at five of the six study sites [U17].

366. Localized points of increased activity can occur at sites of penetrator impacts or close to a penetrator that has remained on the surface and been subject to corrosion. The concentration of DU can be very high at these points, but the extent of the increased activity is very limited, normally within a radius of 1 m, and the total amount varies widely, being in the range 0.01–10 g of DU per kilogram soil. Beneath these points, the activity levels are measurable in soil down to a depth of 10–20 cm or more, with the activity concentration decreasing with increasing depth [U20]. The penetrators recovered had decreased in mass by 10–15% because of corrosion. This has important implications for decontamination approaches as well as for possible future migration into groundwater. DU was not present in any of the groundwater or drinking water samples [U17].

367. Airborne DU particles were detected at two of the six sites. While these particles may have become airborne from on-site digging operations, the finding highlighted the possibility of exposure pathways associated with soil disturbance at DU sites. The overall exposure to DU decreases with time as the exposure via airborne contamination from resuspension of DU dust on the ground surface decreases with time. On the other hand, the probability of DU migration in soil increases with time, owing to the corrosion of DU penetrators [U17]. Many penetrators were found to be heavily corroded, and given a similar rate of corrosion, those penetrators still on the surface may have more or less disappeared from the environment (as solid objects) within 10–20 years. What happens in the case of penetrators buried deep in the ground is not yet known.

368. Uranium concentrations were within the normal range for uranium concentration in drinking water. The concentrations of uranium in air samples were also varied within the normal range, even though they were in the upper part of that range. The UNEP mission to Kosovo in 2000 found that lichen appears to be a bioindicator of airborne DU contamination.

369. *Iraq.* At the time of writing, there were no conclusive results publicly available from assessments of DU levels in the environment in Iraq. Also, the amount of DU munitions used and the sites of impact in the 2003 conflict are unknown. No conclusions on the current situation regarding public exposure due to DU in Iraq can be drawn at present. Preliminary surveys of "hot spots" in Iraq have not detected environmental contamination with DU, but contamination is still anticipated to be found, as many of the destroyed Iraqi tanks and armoured personnel carriers were hit by DU rounds, normally 2–7 times per armoured vehicle. These vehicles are therefore expected to have extensive DU contamination in the form of dust and large fragments [U19]. Urine analysis in United States personnel who served in the conflict has been inconclusive regarding exposure to DU [M24].

(ii) Contaminated sites in the Russian Federation

370. The Russian Federation inherited from the former Soviet Union several thousand square kilometres of radionuclide-contaminated land and some tens of petabecquerels of radioactive waste. Environmental contamination began and was particularly intensive in the early years of the "Atomic Project" activities initiated in the mid-1940s [V10]. At present in the Russian Federation, about 650 million cubic metres of liquid and solid radioactive waste with a total activity of approximately 7.4×10^{19} Bq (2 billion curies) have been accumulated. In addition, approximately 12,000 t of spent nuclear fuel, with a total activity of about 3×10^{20} Bq (8.2 billion curies), are kept at the sites of Minatom and other agencies in the Russian Federation [L2].

371. The total land area contaminated with radionuclides as a result of activities of the Minatom enterprises is about 480 km^2. About 15% of the total area contaminated with radionuclides has gamma radiation exposure rates of above 2 μGy/h [L2]. More than 90% of this land, i.e. 65.7 km^2, was contaminated as a result of the accident at the Mayak complex in 1957 [V10]. The main sites and contaminated areas are described in table 45. An area of about 0.26 km^2 was restored in the period 1996–1999, and rehabilitation of 13.5 km^2 of contaminated land is planned for the period 2001–2010 [L2].

372. At uranium ore mining and milling enterprises, more than 300 million tonnes of solid waste (in dumps of barren rocks and unspecified ores, etc.) and about 60 million cubic metres of liquid waste (in tailings dumps) have accumulated up to the present time. Their total activity (due to radionuclides of uranium and its decay products) is about 7×10^{15} Bq. The total area occupied by the dumps is 9.871 km^2 [L2].

373. Chemical and metallurgical enterprises for nuclear material and fuel element production have accumulated more than 600,000 m^3 of liquid radioactive waste and about 5 million tonnes of solid radioactive waste, containing radionuclides of uranium, thorium and their decay products with total activity of over 1.6×10^{14} Bq (4,200 Ci). The area of land contaminated with radionuclides is 1.868 km^2, including 0.464 km^2 with exposure rates in the range 2–10 μGy/h (200–1000 μR/h).

374. In 1999 there were 50 operating nuclear research reactors and critical or subcritical assemblies in the Russian Federation, 53 facilities whose operation had been suspended

or that were in the process of decommissioning, and 6 facilities under construction. Spent nuclear fuel from the research facilities was concentrated mainly at the following sites: the Russian Research Centre Kurchatov Institute; the Institute of Physics and Power Engineering; the Research Institute of Atomic Reactors; the Sverdlovsk Branch of the Research and Development Institute of Power Engineering; the St. Petersburg Institute of Nuclear Physics of the Russian Academy of Sciences; and the Karpov Physical and Chemical Research Institute's branch in Obninsk. The interim storage facilities for spent nuclear fuel are 80% filled on average [L2].

375. At the Mayak Industrial Association, studies were carried out on Karachai Lake, which is being filled with soil. Beginning in 1951, the lake was used for the discharge of medium- and high-level liquid radioactive waste. Stage-by-stage remediation of the water reservoir was started in 1988. At present, as a result of the remediation actions, the average area of Karachai Lake has been reduced by a factor of over 3 (to 100,000 m^2), which has significantly reduced the emanation of radioactive aerosols from the water surface and shoreline and their subsequent transport by wind. This work is soon to be completed [L2].

376. At the Mining and Chemical Complex, two of the three uranium–graphite production reactors have already been shut down. Many years of reactor operation led to the accumulation of radioactive silts in cooling and storage ponds, and also caused contamination of the Yenisei River flood plain. Contamination levels in the Yenisei flood plain began to decline when the reactors with once-through cooling were shut down. Dose rates in the range 0.08–0.4 μSv/h have been measured in populated areas along the Yenisei River. As a result of the shutdown of these once-through reactors, radionuclide discharges into the Yenisei River have decreased by a factor of over 10, and the present exposure rate at the water surface does not exceed allowable values, even at the discharge point [L2].

377. Up to 2000, the Russian Navy had withdrawn 184 nuclear submarines from service. Of these, 108 were in the north-west part of the country (the Murmansk and Archangel regions) and 76 were in the Far East (Primorsk and the Kamchatka region). Spent nuclear fuel was not unloaded from most of the submarines. A number of the nuclear submarines were withdrawn from service over 10–15 years ago, and defects in the vessels' structures have appeared during this long period afloat. The nuclear submarines with spent nuclear fuel on board represent a serious potential radiation hazard to the environment [L2, V10].

(iii) Contaminated sites in the United States

378. The main contaminated sites in the United States are usually related to the mining of uranium and of other products that have uranium associated with the ore (such as phosphate rocks), to the processing of monazite, to industries dealing with radium, to fuel preparation for nuclear power plants and to research institutions associated with defence programmes.

379. The United States Environmental Protection Agency (EPA) coordinates a project aimed at identifying and cleaning up contaminated areas throughout the country. It has listed 84 sites contaminated with radionuclides; of these, 61 are currently on the EPA's National Priority List. Of these, 14 sites are directly linked with United States nuclear military programme operations (i.e. USDOE sites): Brookhaven National Laboratory, New York state; Feed Material Production Center, Ohio; Hanford Areas 100, 200 and 300, Washington state; Idaho National Engineering Laboratory, Idaho; Lawrence Livermore National Laboratories, California; Monticello Mill Tailings, Utah; Mound Plant, Ohio; Oak River Reservation, Tennessee; Paducah Gaseous Diffusion Plant, Kentucky; Rocky Flats Plant, Colorado; Savannah River Site, South Carolina; and Weldon Spring, Missouri. Four sites are related to the production of radium devices and products, and eight sites are related to NORM, mainly phosphate ore processing and heavy-metal smelting. About 25 sites have been contaminated by improper waste disposal or by the use of waste as landfill; some of these sites are inside military installations. The main concern for such sites is related to the public exposure due to possible contamination of groundwater. For the other sites, the origin of the radioactive contamination is not clear, except for one site, reported to have been contaminated as a result of radiopharmaceutical manufacture [E5]. A large national programme called the Superfund targets the clean-up of hazardous contaminated sites and is conducting recovery operations at most of the sites listed; for some of them remedial operations have already been completed.

(iv) Contaminated sites in the European Union

380. The Dounreay nuclear site, located on the north coast of Scotland, United Kingdom, was responsible for the release of an unknown quantity of approximately sand-sized fragments of irradiated nuclear fuel during the late 1950s, 1960s and 1970s. The first Dounreay hot particle to be formally identified was recovered from the Dounreay foreshore in 1983. A further single particle was recovered from Sandside Beach the following year. Particles have been detected and removed from the Dounreay foreshore regularly since 1984 and from the offshore sediments since 1997. Over 1,200 individual particles have since been found in the littoral (intertidal) and marine environments in the vicinity of Dounreay, including Sandside Beach (1 km west of Dounreay), the Dounreay foreshore, Dunnet Beach and Murkle Beach (both approximately 25 km east of Dounreay), and in marine sediments adjacent to the Dounreay site. In addition, 86 particles have been found on the Dounreay site itself (table 46).

381. Particles are detected in the environment by their ^{137}Cs gamma activity, but the total activity is dominated by the beta emitters ^{90}Sr and its associated ^{90}Y. The particles were

produced during the reprocessing of fuel at Dounreay during the late 1950s, 1960s and 1970s. Two main types of particle, produced from Materials Test Reactor and Dounreay Fast Reactor fuel, have been identified. Materials Test Reactor particles, which make up ~80% of the total recovered, were produced as a result of fault conditions during milling and cropping operations, prior to reprocessing. These milling activities stopped at Dounreay in 1973. Dounreay Fast Reactor particles were most likely produced during combustion incidents in the dissolution cycle during reprocessing. Several such incidents are known to have occurred between 1969 and 1972. Very few particles are found on publicly accessible beaches, and those which are found are small and are promptly removed. Although the risks to members of the public from the presence of particles in the environment are small, they are a problem of public concern [D5, T8].

382. No information has been found on sites in other countries of the European Union contaminated as a result of military activities, except for those related to former uranium mining activities.

(v) Dumping of radioactive waste in the sea

383. Radioactive waste has been dumped in the Arctic Sea, the North Atlantic, the North Pacific and the West Pacific (figure XXX). At present, the total activity of waste dumped in these regions is estimated to have decreased to a total of about 4×10^{13} Bq. This information is contained in the relevant IAEA database [I11]. Doses to critical population groups in coastal areas of the Arctic, North Atlantic and Far East regions of the Russian Federation due to the consumption of seafood products containing radionuclides were shown not to exceed 10^{-4}–10^{-3} of natural radiation background exposure [L2].

384. *Kara Sea* [I11]. In 1992, it was reported that the former Soviet Union had dumped radioactive waste in the shallow waters of the Arctic Seas for over three decades (figure XXXI). The International Arctic Seas Assessment Project (IASAP) was launched by the IAEA in 1993 with the objectives of assessing the current environmental situation associated with the radioactive waste dumped in the Kara and Barents Seas and examining possible remedial actions.

385. The total amount of radioactive waste dumped in the Arctic seas was first estimated by the Russian Federation to be approximately 90 PBq at the time it was dumped. Items disposed at sea included: six nuclear submarine reactors containing spent fuel; the shielding assembly from an icebreaker reactor, which contained spent fuel; ten nuclear reactors without fuel; and solid and liquid low-level waste. Of the total inventory, 89 PBq came from high-level waste comprising reactors with and without spent fuel. Solid waste, including the above reactors, was dumped in the Kara Sea, mainly in the shallow fjords of Novaya Zemlya, where depths at dumping sites ranged from 12 to 135 m, and in the Novaya Zemlya Trough, at depths of up to 380 m. Liquid low-level waste was released into the open Barents and Kara Seas. On the basis of reactor operating histories and calculated neutron spectra, the estimate of the total radionuclide inventory of the high-level radioactive waste at the time it was dumped has been revised to 37 PBq. The corresponding inventory of high-level waste dumped at sea was estimated to be 4.7 PBq in 1994, of which 86% were fission products (main radionuclides ^{90}Sr and ^{137}Cs), 12% activation products (main radionuclide ^{63}Ni) and 2% actinides (main radionuclide ^{241}Pu).

386. The high-level radioactive waste dumped in the Kara Sea and adjoining fjords was in discrete packages, which are expected to leak at some time in the future. They therefore constitute a potential chronic exposure source where the concern relates to future increments of dose to exposed individuals. The open Kara Sea has relatively low levels of artificial radioactivity compared with some other marine areas. Measurements of environmental materials suggest that the annual individual doses due to artificial radionuclides in the Kara and Barents Seas are in the range 1–20 μSv.

387. In two fjords where both high- and low-level wastes were dumped, elevated levels of radionuclides were detected in sediments within a few metres of the low-level waste containers, suggesting that some had leaked. However, this leakage has not led to a measurable increase of radionuclides in the outer parts of the fjords.

388. Calculations of individual doses were undertaken for time periods covering the projected peak individual dose rates for three scenarios and for the following population groups: *(a)* groups living in the Ob and Yenisei estuaries and on the Taimyr and Yamal peninsulas, with habits typical of subsistence fishing communities in other countries with Arctic coastlines; *(b)* a hypothetical group of military personnel patrolling, for 100 hours in a year, the foreshores of the fjords containing dumped radioactive material; and *(c)* a group of seafood consumers considered representative of the northern Russian population situated on the Kola Peninsula. The calculated peak doses to members of these groups due to all sources are shown in table 47.

(vi) Accidental losses of radioactive material at sea

389. Besides the reported events of planned dumping of radioactive material in the sea, there were also several events that included the loss or the release of radioactive material in the sea. These events are summarized in table 7 of annex C of the UNSCEAR 2008 Report and include the following [I17]:

(i) Six nuclear submarines have been lost since 1963 at various sites in the Atlantic Ocean: two from the United States Navy—Thresher in 1963 (one nuclear reactor, 1.15 PBq) and Scorpion in 1968 (one nuclear reactor, 1.3 PBq, and two nuclear warheads); three from the Navy of the former Soviet Union—K-8 in

1970 (two nuclear reactors, 9.25 PBq, and a nuclear warhead, 30 GBq), K-219 in 1986 (two reactors, 9.25 PBq) and K-278 Komsomolets in 1989 (reactor core, 3.59 PBq); and one from the Russian Federation—K-141 Kursk in 2000 (two nuclear reactors, 1–2 PBq). With the exception of the accident involving the Russian submarine Kursk, the depth at the sites of the accidents, below 1,500 m, has not permitted the recovery of the submarines or their nuclear reactors.

(ii) Nuclear weapons have been designed to be carried on submarines, surface ships, aircraft and rockets. There are seven recorded accidents that have resulted in the confirmed loss of one or more nuclear weapons.

(iii) There have been four recorded accidental re-entries of nuclear powered satellites and one recorded accidental re-entry of a spacecraft. Four of these accidents resulted in the actual or potential release of radionuclides into the environment.

(iv) There have been two recorded incidents where radioisotope thermoelectric generators (RTGs) have been lost at sea, both occurring near the eastern coast of Sakhalin Island in the Sea of Okhotsk and both involving emergency disposals of the RTGs during transport by helicopter. In the first incident, which occurred in 1987, the RTG disposed of contained about 25.3 PBq of ^{90}Sr. The second RTG was disposed of in 1997 and contained about 1.3 PBq of ^{90}Sr.

390. Sealed radiation sources are widely used in the marine environment in association with oil and gas exploration and extraction. In some instances the well logging tool and drill string containing the sealed source become stuck in the drill hole and tool recovery is not feasible. The equipment is generally left in place and the hole is closed/sealed. This results in situations where radioactive material could enter the marine environment. In general, these losses have occurred deep in the sediment. The nature of the containment as well as the location of the loss are such that, in general, radionuclide release could occur only after a long period of time. The IAEA database on sealed radiation sources lost in the sea includes about 150 items [I17].

(vii) Other sources of public exposure

391. Since the start of the space age in 1957, radiation sources have been used on board spacecraft for power generation, for thermal control, and in subsystems and instruments (figure XXXII). While electricity for spacecraft has predominantly been produced by photovoltaic cells, there are occasions when, owing to mission criteria (e.g. high power requirements, insufficient solar energy flux in deep space or requirements for planetary landing), the use of solar power is impractical. In such cases, nuclear power sources have been used. To date, only the former Soviet Union, the Russian Federation and the United States have utilized nuclear power systems in Earth orbit or beyond [U44].

392. The United States launched one thermoelectric reactor in 1965. The reactor was shut down after 43 days of operation and placed in a long-term "storage" orbit (an orbit with an estimated orbital decay time of longer than 400 years). The former Soviet Union launched 31 thermoelectric reactors between 1970 and 1988. Their lifetimes ranged from 0.1 to 293 days. Two thermoionic reactors were launched by the former Soviet Union in the period 1987–1988. Their operational lifetimes were 142 and 343 days. It should be noted that no nuclear reactors have been launched since 1988. In addition to nuclear reactors, RTGs have been used as spacecraft power sources. The United States launched 25 missions using 43 RTGs as power sources, two of them using ^{210}Po and the others ^{238}Pu. The former Soviet Union launched two missions with RTGs using ^{210}Po and one mission with four RTG units using ^{238}Pu [U44].

393. Radioisotope heating units (RHUs) utilize radioactive decay to provide heat to surrounding satellite systems and instruments. RHUs have been used on board deep-space probes (i.e. space probes operating beyond the asteroid belt), such as the United States New Horizons probe to Pluto, launched in 2006, and on board planetary landing craft such as the Lunokhod lunar rovers of the former Soviet Union and the United States Mars Exploration Rovers. RHUs are usually small in size and typically produce approximately 1 W of thermal power. Depending on the size of the spacecraft, the number of RHUs used can vary.

394. The current status of these devices is shown in figure XXXIII. Radioactive sources have also been used on board satellites and launch vehicles in applications such as triggering launch vehicle flight termination systems, calibration of on-board instruments and scientific experiments. As an example, the Mars Exploration Rovers (launched in 2003 and still operational as of April 2008) each carry a Mössbauer spectrometer, which uses a small amount of ^{57}Co, and also an alpha particle X-ray spectroscope. Sources of this type are small, and their impact on the environment is considered minimal [U44].

395. In eight cases all or part of the nuclear system re-entered the earth's atmosphere, and there have been two situations where environmental contamination occurred. The first was in April 1964, when the United States SNAP 9A satellite burned up during re-entry. In August 1964, plutonium was detected in the stratosphere (at a height of 32 km), and in May 1965, it was detected at aircraft altitude. In November 1970, it was estimated that some 5% of the original plutonium was still in the earth's atmosphere. Plutonium was eventually detected on all continents and at all altitudes—the concentration in the southern hemisphere was about four times higher than in the northern hemisphere. The second event was in 1978, when the Cosmos-954 satellite of the former Soviet Union came down over Canada, leading to a track of radioactive residues some 500 km long. Some

50 other objects have been recovered. Other satellites or parts of satellites have fallen into the oceans, and one was recovered intact [E1].

396. Reports of accidents involving unconventional orphan sources in the new States that resulted from the dissolution of the Soviet Union have caused particular security concerns. The new States, some of which were not even aware of the existence of such sources, exercised no control over them. Many orphan sources have also been found on former military bases. The resulting exposures are described in annex C. Notable cases of particular concern are abandoned thermoelectric generators containing powerful radioactive sources of ^{90}Sr, which were introduced in the 1970s for dual civilian and military use. RTGs were used in various civilian and military applications, for example to power navigational beacons and communications equipment in remote areas. They usually hold over 1.5 PBq of ^{90}Sr. RTGs were widely used in the former Soviet Union for such applications as generating electricity, heat and battery power for remote communication systems. These types of generator have also been built in the United States, and their radioactive content is more or less of the same order of magnitude. A large number of navigational beacons powered by these RTGs were operated in the Arctic area from Novaya Zemlya to the Barents Straits. In Alaska, United States, several generators were located in the Burmont area. Many RTGs are now being recovered and their sources are being recycled. The first abandoned RTG was found and recovered from the riverbed of the Ingury River in the Republic of Georgia. Two other RTGs were recovered by the IAEA in a remote forested area of north-west Georgia in 2001. RTGs were also found in Tajikistan, dumped in an abandoned building and completely unsecured. A number of RTGs have also been recovered in Belarus [G13, I35].

397. In the period of 2004–2005, a bilateral project between Norway and the Russian Federation decommissioned 96 RTGs from north-western Russia. It is estimated that about 760 RTGs primarily used as lighthouse energy sources still remain along the northern Russian coast. An analysis of radiation protection issues related to decommissioning RTGs has shown that a safe decommissioning practice is unlikely to result in significant radiation exposure of human populations, with a worst case scenario being direct contact with an exposed ^{90}Sr heat source [S34].

(c) Summary on public exposure due to military uses of atomic energy

398. Activities, practices and events involving military and defence uses of sources of radiation have led to releases of radioactive material into the environment with resulting exposures of human populations. The main contribution to the global collective dose resulting from man-made sources has come from the testing of nuclear weapons in the atmosphere. This practice occurred between 1945 and 1980. Each nuclear test resulted in an unconstrained release to the environment of substantial quantities of radioactive material. These were widely dispersed in the atmosphere and eventually deposited everywhere on the earth's surface.

399. Historically, the Committee has given special attention to the evaluation of exposures due to atmospheric nuclear weapons testing. Numerous measurements of the global deposition of ^{90}Sr and ^{137}Cs and the presence of these and other fallout radionuclides in the human diet and the human body have been made since the time tests took place. The worldwide collective dose resulting from this practice was evaluated in the UNSCEAR 1982 Report [U9], and a systematic listing of transfer coefficients for a number of fallout radionuclides was given in the UNSCEAR 1993 Report [U6].

400. Although the total explosive yields have been divulged for each test, information concerning the fission and fusion yields remains suppressed for the most part. Some general assumptions have been made to estimate the fission and fusion yields of each test in order to estimate the amounts of radionuclides produced in the explosions. The estimated total fission yields from all individual tests is in agreement with the estimate of global deposition of the main fission radionuclides ^{90}Sr and ^{137}Cs, as determined by worldwide monitoring networks [U3].

401. With improved estimates of the production of each radionuclide in individual tests and using an empirical atmospheric transport model, it has been possible to determine the time course of dispersion and deposition of radionuclides and to estimate the annual doses due to various pathways in each hemisphere. In this way it has been estimated that the world average annual effective dose reached a peak of 110 μSv in 1963 and has since decreased to about 5 μSv (and now results mainly from residual levels of ^{14}C, ^{90}Sr and ^{137}Cs in the environment). The average annual doses are higher than the global average by 10% in the northern hemisphere (where most of the testing took place) and are much lower in the southern hemisphere. Although there was considerable concern at the time of testing, exposures in fact remained relatively low, reaching at most about 5% of the background level due to natural radiation sources.

402. Exposures of local populations living in areas around the test sites have also been assessed using available information. The level of detail is still not sufficient to document the exposures with great accuracy. Attention to local conditions and consideration of the potential for exposure were not great in the early years of the test programmes. However, dose reconstruction efforts are proceeding to clarify this issue and to document the local and regional exposures that occurred. Local and regional doses may have been very different from the exposure of global fallout. An example is shown in figure XXXIV, where results for ^{137}Cs deposition are presented for the tests in Nevada and for the contribution from global fallout [S23].

403. Underground testing caused exposures beyond the test sites only if radioactive gases leaked or were vented. Most underground tests had a much lower yield than atmospheric tests, and it was usually possible to contain the debris. Underground tests were conducted at the rate of 50 or more per year between 1962 and 1990. Although it is the intention of most countries to agree to ban all further tests, both atmospheric and underground, the treaty to this effect has not yet come into force. Further underground testing occurred in 1998 in India and Pakistan, and in 2006 in the DPRK. Thus it cannot yet be stated that the practice has ceased. Underground testing resulted in a large global burden of radioactive material, and in particular of plutonium, albeit in underground environments. The contribution of this material to future population exposure is uncertain. Currently these residues are not expected to expose members of the public, because they are buried deep underground, and, because of the high temperature reached during the tests, they were fused within the matrix of host rock in an apparently stable and insoluble form.

404. At present there is great concern regarding the reuse of nuclear test areas, since some are being reoccupied. Residues in some environments, for example in localized areas at the Semipalatinsk test site, may be considerable, while in others, such as the Mururoa and Fangataufa Atolls, the residues will not contribute more than a fraction of the normal background exposure to a population eventually occupying the site. For other sites still, such as the Marshall Islands and Maralinga, exposures will be highly dependent on the habits of the populations occupying the area.

405. During the time when nuclear weapons arsenals were being built up, and especially in the earlier years (1945–1960), there were releases of radionuclides and exposures of local populations downwind or downstream of the military nuclear installations. Since monitoring of releases was limited and there was little recognition of the potential risks, present evaluations of exposure must be based on dose reconstructions. Results are still being obtained that document this experience. Practices have greatly improved and arsenals are now being reduced.

406. The military use of DU has led to the contamination of large areas with residues from munitions in several locations, for example Kosovo, former Serbia-Montenegro, Bosnia and Herzegovina, Kuwait and Iraq. This fact has created serious concern that members of the public could be exposed to such residues. A large international effort to assess the consequences of this contamination has been performed, and the main conclusion is that, except for a few specific scenarios (such as the long-term handling of lumps of DU), exposures are expected to be low. It is very unlikely that the long-term behaviour of DU with regard to the leaching and transport of corroded DU lodged in the ground and its potential migration could cause any impact on underground water sources. An assessment of the DU residues in Iraq has not yet been performed.

E. Historical situations

407. Some experiments using atomic weapons were carried out that were not related to military activities. However, these operations would not be allowed today under current international conventions.

408. *Nuclear explosions for peaceful purposes.* Over a period of 24 years, 128 nuclear explosions for peaceful purposes were conducted at 115 sites in the former Soviet Union—in Russia, Kazakhstan, Uzbekistan, Turkmenistan and Ukraine. The first was in 1965 at the Semipalatinsk test site, in the Chagan River channel, to create a water reservoir, and the last was in 1988, near the town of Kotlas. The overall quantity of fission fragments was about 100 kg. Of 108 camouflet explosions,[3] 76 were fully contained. In 26 cases there was radioactive gas leakage (blasts showed pressure efflux), and one explosion, Kraton-3, resulted in the release of radioactive products. The explosion sites and their technical purposes are shown in figure XXXV. The total energy yield of peaceful nuclear explosions in Russia reached 0.75 Mt, or 2% of the value for all underground nuclear explosions in the former Soviet Union.

409. Radioactive traces and contamination of soil and vegetation cover are very rare. Some of these 128 events were single excavation explosions. Five of these, such as the Taiga test, led to the contamination of adjacent areas, requiring remediation. The Taiga test was an attempt to create a canal; this resulted in a radioactive trace 25 km in length. An accidental release from the Kraton-3 test caused the formation of a trace 31 km in length [V10]. The underground nuclear explosion Kristall took place in 1974. Its purpose was to construct a reservoir dam for diamond enrichment plant tailings. Explosions of this type are accompanied by the formation of craters and are characterized by significant releases of radioactive products into the environment. Because of the heavy radioactive contamination, all further work at the Kristall site was stopped. In 1990 a water-filled crater, 60 m in diameter and 6 m deep, still existed at the location of the explosion. During clean-up operations in 1992, the crater was filled with barren rock from the Udachnaya diamond field and was covered with an artificial mound about 100 m in diameter and 7–20 m in height [G5].

410. Kazakhstan's low population density, vast territories that are unsuitable for farming and considerable reserves of minerals made the country a convenient location for the development and production of defence technology and armaments. Apart from the Semipalatinsk test site, there are three other test sites in Kazakhstan where underground nuclear explosions were conducted for peaceful purposes. The radioecological situation at the three sites is not considered serious for the population or the environment. However, the radioecological situation at the Koshkar-Ata storage facility for waste is of major concern [C14].

[3] Camouflet: a cavern caused by a subterranean explosion.

F. Exposure from accidents

411. Several accidents have included the release of nuclear or radioactive material to the environment, leading to exposure of members of the public. In the present report, the Chernobyl accident, which occurred in 1986, is described in annex D, "Health effects due to radiation from the Chernobyl accident", and other accidents, such as the Kyshtym accident of 1957, the Windscale accident of 1957, the Three Mile Island accident of 1979 and the Tomsk accident of 1993, are described in annex C, "Radiation exposures in accidents". There have also been accidents with orphan sources that involved exposures and fatalities among members of the public; these accidents are also described in annex C.

G. Summary on public exposure

412. Exposure to natural sources of radiation is an unavoidable fact of the human condition. The single main source of exposure is the inhalation of radon gas. The estimates of the global average per caput values of exposure to natural sources of radiation are essentially the same as in the UNSCEAR 2000 Report. The estimated value of worldwide average annual exposure to natural radiation sources remains at 2.4 mSv. The normal range of exposures to the various components is presented in table 12. As described earlier in this annex, the dose distribution worldwide is expected to follow approximately a log-normal distribution, and most exposures would be expected to fall in the range 1–13 mSv/a.

413. The interest in exposures to NORM is increasing as new situations are identified and corresponding dose assessments are performed for specific scenarios. Doses of up to a few millisieverts per year may be expected for some specific scenarios, such as the use of sludges from water treatment as fertilizers, or the use of wastes and other materials as landfill or building materials. There is not yet a consistent approach to characterize inventories of sources and to estimate potential and actual exposures in order to extrapolate to a worldwide dose assessment. The Committee encourages the continued development of inventories and methodologies for dose assessment in order to make possible a broader view of the scenarios in a global context.

414. Residues due to conventional mining operations also lead to huge amounts of material with enhanced levels of NORM, and these represent a challenge regarding both the disposal of the residues and site restoration. The large diversity of ores containing low levels of nuclides from the uranium and thorium families, which may be concentrated in products, by-products and wastes, complicates the problem. The detailed picture of worldwide exposure is far from complete. As with other contaminated sites, the main radioactive materials are still under the control of operators, and most situations pose mainly potential exposure for members of the public. Although the public exposure is not expected to be high, some areas with enhanced levels of NORM may involve the low-level exposure of large numbers of people. A large effort is needed to reach an international consensus on ways of addressing this situation to keep the public exposures under control at levels compatible with exposures to other sources.

415. One continuing practice is the generation of electrical energy by nuclear power reactors. During the routine operation of nuclear installations, releases of radionuclides are low and radiation exposures must be estimated using environmental transfer models. For all fuel cycle operations (mining and milling, reactor operation and fuel reprocessing), the local and regional exposures are estimated to be 0.72 man Sv/(GW a). For the present world nuclear energy generation of 278 GW a, the collective dose per year of practice is of the order of 200 man Sv. The assumed representative global value for the local and regional populations of nuclear installations is about 250 million persons, and the annual per caput dose to this population is less than 1 μSv. The collective doses due to globally dispersed radionuclides are delivered over very long periods and are expressed for the projected maximum future population of the world. If the practice of nuclear power production were to be limited to 100 years at the present capacity, the maximum annual per caput effective dose to the global population would be less than 0.2 μSv. This dose rate is minute compared with that due to natural background radiation.

416. Releases of isotopes produced and used in industrial and medical practices have been discussed and appear to be associated with rather insignificant levels of exposure of the general public. Except in the case of accidents, in which more localized areas can be contaminated to significant levels, there are no practices that result in important exposures as a result of radionuclides released to the environment.

417. While doses due to nuclear power production have been extensively described and reported, this is not the case for military uses and activities. Furthermore, some historical estimates assigned doses to nuclear power production (such as those due to the generation of radioactive waste and to uranium mill tailings, among others) that were in part also related to military activities.

418. The main contribution to the global collective dose due to man-made sources has come from the testing of nuclear weapons in the atmosphere. This practice occurred between 1945 and 1980. These tests have led to local, regional and global exposure because of the worldwide dispersion of radioactive material in the atmosphere, material that was subsequently deposited everywhere on the earth's surface. It has been estimated that the worldwide average annual per caput effective dose reached a peak of 110 μSv in 1963 and has since decreased to about 5 μSv (mainly due to residual levels of ^{14}C, ^{90}Sr and ^{137}Cs in the environment). The average annual doses are higher than the global average by 10% in the northern hemisphere, where most of the testing took place, and are much lower in the southern hemisphere.

The underground testing also left an environmental legacy of plutonium in the subterranean environment of all the sites involved in such tests. Although currently any exposure to these sources is low, exposure scenarios for the distant future are very uncertain.

419. Besides areas related to atomic bomb production and testing, early uses of radiation also left a legacy of numerous small contaminated sites around the world. Efforts to decontaminate these sites and return them to public use have been a focus of attention in many countries. Several types of contamination are involved, many related to industrial uses of naturally occurring radionuclides or to old mining areas. Exposures and collective doses are site-specific; once the areas are defined, exposures can be constrained. There is a general tendency for exposures to fall with time because of clean-up procedures, although for some sites there will be a need for long-term follow-up because of the long half-lives of the radionuclides involved. In the United States alone, just over 5,000 remediation projects have been completed to date at various USDOE facilities, and another 5,400 remain. Some 1,186 sites are currently under decommissioning. As site release criteria are usually developed with a focus on critical group exposure, real doses to the public will depend on whether released sites are actually occupied. In general, individual doses estimated for a hypothetical critical group are in the range 0.3–1.0 mSv. Regional average individual doses will be at least one order of magnitude lower, and the contribution to the worldwide population doses will most probably be negligible.

420. The enrichment process for natural uranium generates a large amount of by-products containing DU. Owing to the properties of this dense metal, it has found civilian and military uses. Military use led to pockets of contamination over large battlefield areas on the territory of the former Yugoslavia and in Kuwait. This has led to great public concern, and consequently considerable work has been done to assess current and potential exposures due to these residues in the environment. Although most areas were cleaned up before release to public access, uncertainties remain on the long-term exposures to specific individuals. This is because of the possibility of penetrators presently buried underground being found following human actions such as digging or ploughing, and of the enhanced corrosion rates observed for penetrators, which could ultimately lead to migration of DU into underground water. However, no significant collective doses are expected to result from either of these pathways.

421. Historically contaminated sites related to the peaceful uses of atomic energy are primarily related to the radium industry. These areas, mainly located in the United States, the European Union and Canada, have already been identified, and most of them have been isolated from the public or have been the subject of decommissioning programmes. Residual exposures are thereby constrained to levels that are compatible with current operational practices. There are also a large number of sites with mining residues associated with nuclear power production worldwide. Large environmental restoration programmes are being undertaken in order to bring the level of exposure in these areas within the range of those considered acceptable for ongoing practices.

422. Possible future practices (such as weapons dismantling, decommissioning of installations and waste management projects) can be reviewed as experience is acquired, but these are all expected to involve little or no release of radionuclides and consequently little or no exposure.

423. A large number of smaller accidents have also resulted in the exposure of members of the public, and many have led to fatalities. Annex C of the UNSCEAR 2008 Report, "Radiation exposures in accidents", discusses this subject in more detail. Most of these accidents resulted in the exposure of small groups of people to radiation from industrial and medical sources that had left institutional control. These accidents have mostly involved relatively small numbers of persons, usually family, close friends or neighbours, but individual doses were in some cases very high.

424. There were also a few situations where this type of accident led to more widespread environmental contamination and to the exposure of larger numbers of people. These include: the Goiânia accident in 1987, with the dispersion within an urban area of a medical ^{137}Cs source; the accident in Mexico in 1983, where a cobalt source for medical purposes found its way into the production of steel used in building material and other objects; and the accident in Taiwan, China, where several residential buildings used material with contamination from a cobalt source. Such accidents led to widespread exposures, and although the collective doses resulting from such events are not high, those individuals who personally manipulated the sources were subject to doses that led in some cases to deterministic effects or even death.

425. Exposure of members of the public to the various sources discussed in this annex has a very wide variability in actual doses and in the contribution of different sources to the overall exposure. As an example, figure XXXVI shows the estimated contribution of different sources to the population exposure of different countries. In describing exposure from different sources, there is no standard pattern followed by different countries. For example, most countries do not have specific data on exposures from consumer products, and therefore such data are not included on their overall assessments. Also, exposures to sources have different time trends in different countries. For example, while in United Kingdom it has been verified that the contribution from various sources has not changed significantly since the 1970s, with natural sources dominating public exposure, in the United States, the average annual per caput dose from medical exposure has increased from 0.54 mSv in 1982 to about 3 mSv in 2006, making medical exposure the largest source of radiation exposure to United States population [J5, M23].

426. A better understanding of the components of the total exposure from different sources on a geographical basis

could change the current exposure assessment and lead to more precise estimates of the distribution of exposures worldwide. Up to now, only the variability associated with exposures to individual sources has been taken into account in worldwide dose estimates. There are, however, circumstances in which the distribution of doses due to one source affects the overall distribution of doses due to other sources. This can be the case, for example, for certain locations where there are high levels of natural radionuclides in the environment and where higher doses due to radon inhalation may be correlated with high doses due to external exposure or food ingestion. Another possible situation is the uneven distribution of nuclear power plants worldwide, which is broadly correlated with the distribution of population.

427. An example of different dose distributions affecting public exposure is given in figure XXXVII, which shows several maps related to different sources of exposure of the public in the United States. It can be seen that concentrations of uranium and thorium are closely correlated with each other and also with external dose rates and radon concentrations. Also, the distributions of nuclear installations and of population density appear to be correlated. The distribution of collective dose contributions may be very different from current estimated distributions, considering specific distributions among the individual quantities involved. This could indicate a need for future revision of the methodology for estimating averages and ranges of population doses worldwide.

III. OCCUPATIONAL RADIATION EXPOSURE

428. The International Labour Organization (ILO) [I62] and the International Basic Safety Standards [I7] define occupational exposure as "all exposure of workers incurred in the course of their work, with the exception of exposure excluded from the Standards and exposures from practices or sources exempted by the Standards" [I62].

429. Various national authorities or institutions have used different methods to measure, record and report the occupational data included in this annex [I25]. The main features of the method used by each country that responded to the UNSCEAR Global Survey of Occupational Radiation Exposures are summarized in table A-15. The procedures for the recording and inclusion of doses differ from practice to practice and from country to country. It must be recognized that differences in monitoring and reporting practices do exist, and these differences may, in particular cases, lead to spurious conclusions being drawn from comparisons between reported data.

430. The criteria applied in different countries to select workers who should be monitored differ considerably. Some countries monitor only the exposed workers, while others also include non-exposed workers in their individual monitoring programmes for various reasons. This can lead to spurious results when attempting to compare levels of exposure in different countries and practices. Moreover, the exposure due to radon is often underreported, since many countries record the dose only when radon concentrations of above 1,000 Bq/m^3 in air are found. There are likely to exist workplaces where radon exposure can deliver significant doses but which have not yet been identified [F15].

431. Occupational radiation exposures have been evaluated by the Committee [U3, U6, U7, U9, U10] for six broad categories of practice: practices involving elevated levels of exposure to natural sources of radiation, the nuclear fuel cycle, medical uses of radiation, industrial uses, military activities and miscellaneous uses (which includes educational and veterinary uses of radiation). The Committee has evaluated five-year average exposures beginning in 1975. The data presented in this annex are for the periods 1995–1999 and 2000–2002. The data from the previous periods are provided for comparison. Table 48 presents the practices for which the occupational exposure has been evaluated.

432. The data in this annex were obtained in much the same way as the data for the UNSCEAR 2000 Report [U3], i.e. by means of a questionnaire, the UNSCEAR Global Survey of Occupational Radiation Exposures. For the current period, a new questionnaire (requesting more detailed information for the period 1995–2002) was distributed to Member States of the United Nations by the UNSCEAR Secretariat. The data have been supplemented by other (usually published) sources of information. For the nuclear power industry, for example, a principal source is the joint databank of the Organisation for Economic Co-operation and Development/Nuclear Energy Agency (OECD/NEA) and the IAEA—the Information System on Occupational Exposure (ISOE) [O14, O19, O20], which serves as a main source of data on occupational exposure resulting from reactor operations for the period 1995–2002. Table A-15 presents the complementary information provided by those States that responded to the UNSCEAR survey.

433. Differences may exist in the procedures used in various countries to categorize workers according to their occupations. This limits the validity of direct comparisons between data compiled in different countries. Where these limitations may be important, they are identified. The extent to which valid comparisons between countries can be made is also influenced by differences in the approaches used to measure and report occupational exposures, e.g. the type of dosimeter used, its minimum detectable level (MDL), the dose entered into records when the measured dose is less than the MDL, and the dose assigned when dosimeters are lost. The approaches used in measuring and reporting

occupational exposures in each of the countries for which data were reported are summarized in table A-15. Where important differences in approach are apparent, caution should be exercised in making direct comparisons between data.

434. In the UNSCEAR 2000 Report, the Committee evaluated occupational exposure for each practice in each country using average values for all workers over five-year periods. The purpose of this annex is to provide more detailed information on occupational exposure related to the different practices, for example to identify job functions and categories of work within each practice that lead to more significant exposures, to identify the contributions of external versus internal exposure to the total effective dose, and to obtain information about the reliability of measurements associated with the accreditation or authorization of monitoring services.

435. About 70% of the countries that reported data have their external dosimetry services accredited or authorized by some national or international regulatory authority. The situation is the very different for internal dosimetry, for which about 25% of the countries have reported that their services are accredited or authorized.

A. Assessment methodology

1. Dose recording

436. In most countries, dose recording and reporting practices are governed by regulations and may differ for various categories of workers depending on the anticipated levels of exposure. The IAEA, in its publications [I7, I13, I14, I16, I27], has provided guidelines on how monitoring data and results should be reported, what dose levels should be recorded, and what documents and records of radiation exposure should be maintained. Although there are guidelines for dose recording, there may be variations from country to country that may significantly affect the reported values of collective dose. The most important differences arise because of the following factors:

- The recording of dose values less than the MDL;
- The technique used for measurement of external radiation exposure, for example thermoluminescent dosimeter (TLD), film, electronic dosimeter, optically stimulated dosimeter or glass dosimeter;
- The assignment of dose values to fill missing periods in the records;
- The evaluation of anomalous results, such as unexpectedly high or low dose values;
- The subtraction of background radiation doses;
- The protocol for determining who in the workforce should be monitored and for whom doses should be recorded in particular categories;
- Whether or not internal exposures are included or are treated separately;
- The reliability of the individual monitoring data.

437. In order to ensure the reliability of dose assessments, some countries have implemented systems to authorize monitoring services based on a set of requirements established by the national regulatory authority, while others apply criteria based on the quality management system for accrediting individual monitoring services [M19].

2. Characteristics of dose distributions

438. The dose distributions presented in this annex follow the same approach as the one described in the UNSCEAR 2000 Report [U3]. The Committee is interested in comparing dose distributions and in evaluating trends. For these purposes, four characteristics of the dose distributions are identified as being particularly useful:

- The average annual effective dose (i.e. the sum of the annual dose due to external irradiation and the committed dose due to intakes in that year), E;
- The annual collective effective dose (i.e. the sum of the annual collective dose due to external irradiation and the committed collective dose due to intakes in that year), S;
- The "collective dose distribution ratio", SR_E (for values of E of 15, 10, 5 and 1 mSv), provides an indication of the fraction of the collective dose received by workers exposed at various levels of individual dose;
- The "distribution ratio for the number of exposed workers", NR_E (for values of E of 15, 10, 5 and 1 mSv), provides an indication of the fraction of the total number of workers exposed at various levels of individual dose.

439. The annual collective effective dose, S, is given by:

$$S = \sum_{i=1}^{N} E_i$$

where E_i is the annual effective dose received by the ith worker and N is the total number of workers. In practice, S is often calculated from collated dosimetry results using the alternative definition:

$$S = \sum_{j=1}^{r} N_j E_j$$

where r is the number of effective dose ranges into which the dosimetry results have been collated and N_j is the number of individuals in the effective dose ranges for which E_j is the mean annual effective dose. The average annual effective dose, E, is equal to S/N. The number distribution ratio, NR, is given by:

$$NR_E = \frac{N(>E)}{N}$$

where $N(>E)$ is the number of workers receiving annual doses exceeding E mSv. Similarly, the annual collective dose distribution ratio, SR, is given by:

$$SR_E = \frac{S(>E)}{S}$$

where $S(>E)$ is the annual collective effective dose delivered at annual individual doses that exceed E mSv.

440. Depending on the nature of the data reported and subject to the objectives of the evaluation (or the topic of interest), the "number of workers" may be those monitored, those who work in workplaces classified as controlled areas, those measurably exposed, the total workforce or some subset thereof. Therefore these derived quantities will always be specific to the nature and composition of the workforce included in the estimation; when making comparisons, caution should be exercised to ensure that like is being compared with like.

3. Estimation of worldwide exposures

441. Inevitably, the data provided in response to the UNSCEAR Global Survey of Occupational Radiation Exposures were insufficient for estimating worldwide levels of dose. Procedures were therefore developed by the Committee to derive estimates of worldwide doses from the data available for particular occupational categories. Two procedures were developed, one for application to occupational exposures arising at most stages in the commercial nuclear fuel cycle and the other for general application to other occupational categories. For the occupational groups involved in practices other than the nuclear fuel cycle, the approach to derive estimates of worldwide doses used in the UNSCEAR 2000 Report is no longer used here. This is because the available data for the last two periods, 1995–1999 and 2000–2002, are not sufficient to derive a reliable number that reflects the worldwide level of exposure. For medical exposure, the number of workers was estimated on the basis of the information from the UNSCEAR Survey of Medical Radiation Usage and Exposures. The Committee has decided to evaluate the worldwide level of occupational exposure for the different practices in the industrial and miscellaneous fields on the basis of the trends in the countries for each practice. The worldwide level of exposure was estimated on the basis of the quantile regression using the median estimated values of the data reported by the countries [K15].

442. In general, the reporting of exposures arising in the commercial nuclear fuel cycle is more complete than that of exposures arising from other uses of radiation. Hence the degree of extrapolation from reported to worldwide doses is less, and this extrapolation can be carried out more reliably than for other occupational categories. Moreover, worldwide statistics are generally available on the capacity and production in various stages of the commercial nuclear fuel cycle. Such data provide a convenient and reliable basis for extrapolating to worldwide levels of exposure. Thus the worldwide annual collective effective dose, S_w, due to a given stage of the nuclear fuel cycle (e.g. uranium mining, fuel fabrication or reactor operation) is estimated from the total of the annual collective effective doses reported by countries multiplied by the reciprocal of the fraction, f, of the world production (uranium mined, fuel fabricated, energy generated, etc.) accounted for by these countries, namely:

$$S_W = \frac{1}{f}\sum_{c=1}^{n} S_c$$

where S_c is the annual collective dose arising in country c and n is the number of countries for which occupational exposure data have been reported. The fraction of the total production can be expressed as:

$$f = \sum_{c=1}^{n} P_c \,/\, P_w$$

where P_c and P_w are the production in the country, c, and in the world, w, respectively.

443. The number of monitored workers worldwide, N_w, in a given year is estimated by a similar extrapolation. Because the data are more limited, the worldwide distribution ratios, $NR_{E(w)}$ and $SR_{E(w)}$, are simply estimated as weighted averages of the reported data. The extrapolations to worldwide collective effective doses and numbers of monitored workers and the estimation of worldwide average distribution ratios are performed for each year. Values of these quantities have then been averaged over five-year periods, except for the last period (2000–2002), which included only three years, and the average annual values are reported in this annex. The Committee has also made projections for exposures for the period 2002–2006 based on extrapolating the trends for each practice over the six periods previously analysed.

B. Natural sources of radiation

444. Enhanced levels of natural background radiation are encountered in many occupational settings, especially in underground mines. Mining involves a large number of workers, and although the data are more limited than those for occupational exposures to man-made sources, the annual collective effective dose has been estimated to be approximately twice as large [U6]. Until implementation of the International Basic Safety Standards [I7], most countries had not been particularly concerned with assessing occupational exposure to natural sources of radiation. Over the last few years, exposures to enhanced levels of natural radiation have become a focus of attention in the field of radiation protection. Title VII of the European Basic Safety Standards [E11] and related guidance [E14] cover those work activities where the presence of natural radiation sources that lead to a significant increase in the exposure of workers and members of the public cannot be disregarded. Besides the European Union countries, others have already implemented radiation protection legislation for NORM.

445. The great majority of the workers exposed to natural sources of radiation are not individually monitored. They include aircrew, workers involved in mineral extraction and processing, and workers exposed to radon in workplaces other than mines. The doses of aircrew are estimated from measurements in the aircraft and also by numerical simulation with computer codes. The occupational exposure of aircrew is controlled through limiting their time in flight [U41]. The workers involved in mineral extraction and processing represent by far the largest occupational group exposed to sources of ionizing radiation. Only a few countries have monitored these workers on a routine basis. Besides mines, there are several other workplaces where workers may receive very high doses due to radon exposure; this has been highlighted in the results of survey programmes conducted in some of these workplaces. Since for many countries these data are not routinely recorded, an extensive review of the literature has been conducted in order to present a more comprehensive picture of occupational exposure to natural sources.

1. Cosmic ray exposures of aircrew and space crew

(a) Aircrew

446. Exposure to cosmic radiation is influenced by many factors, as was discussed in section II.A.1 of this annex. The International Commission on Radiological Protection (ICRP), in its Publication 60 [I47], has identified airline flight crews as an occupationally exposed group. By the early 1990s, the European Commission had agreed that a comprehensive survey should be undertaken of the radiation environment produced by cosmic rays at aviation altitudes, and an extensive programme of experimental and theoretical studies was supported [E9, S31]. The European Union has established standards for the protection of workers exposed to natural radiation [E10]. These standards explicitly include flight personnel, who could receive an annual dose due to cosmic rays of over 1 mSv. Since 2002, the European Union countries have recorded the associated doses in an occupational exposure database on a regular basis.

447. In recent years, new experimental studies have been conducted of the monitoring methodology for estimating the low- and high-linear-energy-transfer (LET) components of the radiation field on board aircraft [B5, S10, S11, S31]. The tissue equivalent proportional counter (TEPC) is the only direct-reading dosimeter that measures both absorbed dose to tissue and radiation quality in terms of linear energy [L14, T1]. Several studies have been carried out to compare the dose estimated on the basis of the results of on-board measurements with the ones estimated by calculations using the computer codes. Good agreement has been observed between the measured values and the calculated ones [B15, B17, B44, F6, L8, L15, O2, S32].

448. A number of computer codes have been developed to estimate aircrew doses according to specific parameters related to the flight routes. A new version of the Civil Aerospace Medical Institute (United States Federal Aviation Administration) computer program CARI-6M calculates, on the basis of an anthropomorphic phantom, the effective dose of galactic cosmic radiation received by an individual on an aircraft flying a user-specified route [N3]. The European Program Package for the Calculation of Aviation Route Doses (EPCARD) is a tool to calculate the effective dose or the ambient dose equivalent and to determine the contribution of the different field components [M8]. The Predictive Code for Aircrew Radiation Exposure (PCAIRE) estimates values for the total ambient dose equivalent or the effective dose. The PCAIRE program is based on experimental results from measurements on board aircraft, and its predictions should agree with the associated measurement results [L6]. SIEVERT, a computerized system for the assessment of exposure to cosmic radiation in air transport, is also a very useful tool [B42, B44].

449. The different programs have been used to calculate route doses for 28 different flights that took place during the period from May 1992 until September 2001. Calculations were performed for both effective dose and ambient dose equivalent. There are relatively larger differences (up to 30%) between the results of the different transport codes for effective dose than between the results for ambient dose equivalent. For the latter quantity, the agreement is within 10–15%. This can be explained by the different assumptions about the galactic proton distribution and the use of a proton radiation weighting factor of 5 in the calculation of effective dose, whereas the corresponding mean quality factor is 1.5 in the calculation of ambient dose equivalent [L15].

450. Since August 2003, 45 airline companies in Germany have routinely assessed the exposure of their personnel by application of computer codes. For the first year of dose registration, from August 2003 to July 2004, the national dose registry for occupational exposure includes data on a total of 31,000 crew members. The collective dose to the group of 60 man Sv contributes more than 50% to the total of the collective dose of all workers in Germany. About the same proportion of collective dose to aircrew is reported by the Netherlands [V3]. As seen in table 49, Germany and the United Kingdom report the largest number of flight personnel among the European Union countries. The average annual dose of the flight personnel varies from 1.3 to 2.5 mSv. None of the reported annual dose values exceeded 6 mSv. The frequency distribution of the individual dose values is bimodal; however, the dose distribution observed for the other categories of work is characterized by an exponential decrease in the number of observations with increasing values of the dose. Table 50 presents the dose estimates for specific flight routes leaving Frankfurt [S38].

451. The number of flight personnel in the United States is approximately 150,000 [U27]. Radiation doses due to individual commercial flight segments typically range from 0.3 to >60 μSv per flight, depending on latitude, altitude and duration. Annual doses range from 0.2 to 5 mSv, depending on flight routes and number of hours flown per year [W4, W5].

452. There are a large number of females in the workforce. Female flight attendants flying both a large number of hours during pregnancy (e.g. 100 hours per month) and only the routes with the highest dose rates (e.g. 0.006 mSv per block hour) would exceed 0.5 mSv to the embryo/foetus (excluding natural background and medical exposures) [W4].

453. Data on the occupational exposure of crew members are presented in the first part of table A-16 and also in table 49. Most of the limited number of data refer to the year 2002. The number of reported monitored workers is 90,540. The reported collective effective dose is 165 man Sv. The reported average effective dose is about 1.8 mSv. The reported average effective dose data are in agreement with the data presented in table 49. In this table, information is provided for the United States, with a workforce of approximately 150,000 [U27]. No changes in terms of the total number of crew in the worldwide workforce have occurred since the UNSCEAR 2000 Report. Assuming that the countries reported in tables 49 and A-16 represent about 80% of the worldwide workforce, the total would be 300,000 workers. The average effective dose for the European countries is about 2 mSv. The average annual flying time is estimated as 600 hours for aircrew in European countries and about 50% more for aircrew in the United States. On the basis of these values, it is assumed that 50% of the workforce is exposed to 2 mSv/a and 50% is exposed to 3 mSv/a. Under these assumptions, the estimated collective effective dose is about 900 man Sv. This value for the collective dose is about the same as that estimated in the UNSCEAR 2000 Report, 800 man Sv [U3]. These doses could be slightly underestimated, if it is assumed that the crew members are also frequent flyers, since most of them receive free air tickets for travel with their airlines. Couriers represent a separate group; they may spend greater total times in flight in the course of a year, but even so are unlikely to incur a dose exceeding 10 mSv in a year.

(b) Space crew

454. At altitudes of between 200 and 600 km and at low inclinations, the major contribution to the absorbed dose is delivered inside the South Atlantic Anomaly (SAA) by the geomagnetically trapped protons and electrons of the radiation belt. The SAA is an area where the radiation belt comes closest to the earth's surface owing to a displacement of the magnetic dipole axes from the earth's centre. In this region, fluxes vary extremely rapidly with altitude, because of interactions of the charged particles with the nuclei of the atoms of the upper atmosphere. The flux in the SAA is anisotropic, with most of the flux arriving perpendicular to the magnetic field lines [R8].

455. The dose measurements for the on-board crew of various missions (first United States Spacelab mission (SL1), Dedicated German Spacelab missions (D-1 and D-2), International Microgravity Laboratories (IML-1 and IML-2), German Mir-92 flight to the Russian space station) show that the doses were in the range 1.9 mSv to around 27 mSv, depending on the mission, as shown in table 51. The main contribution to the dose came from the protons of the SAA; its value increases with altitude and decreases with increasing solar activity and mass shielding [R6, R7, R8].

456. The fraction of the dose on the Mir space station due to the SAA on an orbit inclined at 51.6° and at an altitude of about 400 km was determined during the Euromir '95 mission. The measurement was performed using an hourly measuring period for 170 h. It was found that the maximum dose due to crossing the SAA was equal to 0.055 mGy. Averaging all the measurements, it was calculated that the mean dose rate inside Mir varied from 0.012 to 0.014 mGy/h, and that half of this value was due to the SAA [D4].

457. Measurements of the cosmic radiation dose inside the Mir space station and the additional dose to two astronauts in the course of their extravehicular activity (EVA) were performed. During an EVA lasting 6 h, the ratio of dose rates inside and outside Mir was measured. During the EVA, Mir crossed the SAA three times. Taking into account the influence of these three crossings, the mean outside/inside dose rate ratio was 3.2. The absorbed dose rate inside Mir was 0.023 mGy/h, while the mean absorbed dose rate during the EVA was 0.073 mGy/h [D12].

458. The dose assessments for various space missions of the former Soviet Union and the United States show that the daily absorbed dose varied between 0.32 and 0.57 mGy, and the daily dose equivalent between 0.62 and 1 mSv. The dose assessment was based on data from dosimeters placed in different locations in the space station. The value for the radiation weighting factor was about 3 at high latitude and decreased to about 1.5 near the equator. This effect is due to the greater geomagnetic protection at low latitudes, where only high-energy particles penetrate the atmosphere. Nearer the poles, there is a higher particle flux with lower mean energy. Variations could be explained by differences in the mass shielding properties at the locations of these detectors [B41].

459. The second flight of IML-2 on Space Shuttle flight STS-65, which was launched on 8 July 1994, was sustained in a 28.45º by 296 km orbit for a duration of 14 days, 17 hours and 55 minutes. The crew doses varied from 0.94 to 1.2 mGy. A reasonable agreement was found between the galactic cosmic ray dose, dose equivalent and LET spectra measured using the TEPC flown in the payload bay and those calculated using models [B3].

460. The Mir-18 mission began in March 1995 [B4]. The absorbed dose measurements for the Mir-18 crew showed that the dose depended on the tasks the crew performed. Estimates were 3.76 $\pm$ 0.18 mGy, 2.87 $\pm$ 0.15 mGy and 3.53 $\pm$ 0.24 mGy for the commander, flight engineer and flight researcher, respectively. Dosimeters were worn at least 80% of the time. The dose values are not corrected for the loss of high-LET particles. The Mir space station was in a 51.65º inclination orbit from 1986 to 2001.

461. Evaluation of individual doses using cytogenetic dosimetry techniques has shown that the yields of dicentrics and centric rings scored after long-term space flights are considerably higher than those scored prior to the flights. In this study, a total of 22 cosmonauts were examined. Some of them were examined after repeated flights. The missions lasted for 4–6 months on average. Individual doses measured using biodosimetry to cosmonauts who showed a reliable increase in the yields of chromosomal-type aberrations after their first flights were estimated to be from 0.02 to 0.28 Gy [F3].

2. Exposures in extractive and processing industries

462. The extraction and processing of radioactive ores are carried out in a number of countries throughout the world. The extractive industries include all forms of mining. Minerals and other natural materials that are not normally regarded as being radioactive may nevertheless contain significant levels of natural radionuclides from the uranium and thorium decay chains. These raw materials, their by-products from processing and the end products produced may lead to exposures in workplaces where there is often no perception, let alone appreciation, among workers of the various relevant radiation protection problems. The main source of exposure in most mining operations is radon. Exposure due to long-lived radionuclides in mineral dusts can, however, be important in certain mining and other situations.

463. Mining is an extensive industry. Employment in the mining industry is changing in several ways for a variety of interrelated reasons: commercial, political, technological, demographic and social. The net effect, however, has been a steady fall in the number of people employed in mining. According to the International Labour Organization, since the early 1990s, when about 25 million people were estimated to be employed in mining (including some 10 million in coal mining), the decline in employment has ranged from steady to more rapid at different times in different regions. By the year 2000, a decline in the number of workers in mining ranging from 32% to about 45% was estimated to have occurred, which would give an estimate of about 6.8 million workers involved in coal mining operations [I39]. The estimated number of underground coal mine workers in China is about 6.05 million [L20]. Mining is still a male-dominated industry. Although more women are now working in all aspects of mining in some countries, any increase in female employment is generally from a very low base.

464. By far the largest category of workers exposed to ionizing radiation are those employed in the extractive and processing industries. A rough estimate of the total number of workers potentially exposed to internal radiation in non-nuclear industry in the European Union is 5,000–10,000. Exposure situations for workers in these industries differ considerably with respect to the type of industry, the conditions in the workplace, the radionuclides involved, and the chemical and physical forms of the matrices in which the radionuclides are incorporated [V1].

465. The main potential sources of occupational exposure in the extractive industries are the natural radionuclides arising from the radioactive decay of the ^{238}U and ^{232}Th series. Exposures may arise via three main routes: *(a)* the inhalation of radon, thoron and their respective progenies; *(b)* the inhalation and ingestion of ore dust; *(c)* external irradiation with gamma rays.

466. Radon is the main source of radiation exposure in most underground mining operations. While several isotopes of radon exist in nature, one (^{222}Rn) dominates in terms of dose to workers. Under some circumstances, ^{220}Rn (thoron, a decay product of the ^{232}Th chain) may also be important. For convenience, unless stated otherwise, "radon" is taken here to mean ^{222}Rn. The short-lived decay products or progeny of radon, rather than the gas itself, are the main cause of exposure, although for control purposes it is often the concentration of the gas that is referenced [C13].

467. Continuous radon and thoron gas measurements along with several particle size distribution measurements were made at 20 locations in a rare earth (monazite) pilot processing plant near Bangkok, Thailand. The measurements were conducted from February 2001 to November 2006. A miniature alpha track detector combining both radon and thoron measurements was used. The radon and thoron concentrations ranged from 15 to 100 Bq/m^3 and 150 to 1,550 Bq/m^3, respectively. The measured thoron range was large at any single location. Near a monazite digesting tank, for example, the thoron concentration in air ranged from 80 to 1,500 Bq/m^3 over the five-year period. The UNSCEAR 2000 Report's conversion factors of 9 nSv/(Bq h m^{-3}) for effective dose from radon and 40 nSv/(Bq h m^{-3}) for effective dose from thoron were used. Several studies document the equilibrium fraction, F_{eq}, for thoron indoors, as 0.02–0.03. The value 0.02 was used in the thoron dose calculation. The F_{eq} used for radon indoors was 0.4. The calculated bronchial dose for individuals who worked in the same location in the rare earth processing facility for 2,000 hours in a year could lead to a calculated annual lung dose of up to 0.7 mSv due to radon and 2.4 mSv due to thoron. The particle size distributions taken over intervals of 1 to 2 months with a miniature integrating particle size sampler showed four peaks, at 5, 150, 400 and 5,000 nm, with 50% of the activity associated with the 150 nm mode [H6]. The results of the SMOPIE project (Strategies and Methods for Optimization of Internal Exposures) indicate that rare earth processing may give rise to annual doses of over 20 mSv [V1].

468. The natural radionuclides involved in any processing technology for natural raw material end up either in the finished products or in the liquid, solid or gaseous waste generated. Depending on their chemical properties, the radionuclides are concentrated or distributed in the end products and in the waste [B19, S20]. The grinding of raw materials may generate fine particles of dust and also make it easier for radon to escape into the workplace air. Processing materials rich in uranium or thorium decay products at high temperatures (e.g. coal combustion) could enrich airborne

dust in some radionuclides of the uranium and thorium series, e.g. ^{210}Po and ^{210}Pb. At very high temperatures (3,000ºC or greater), other radionuclides of the uranium or thorium series may also sublimate. For example, ^{228}Ac may sublimate during welding from welding rods doped with ^{232}Th [B19, I18, I26].

469. In a survey programme involving six underground coal mines in Baluchistan, Pakistan, radon measurements were carried out to estimate the workers' doses due to radon exposure. Radon concentrations varied from 121 to 408 Bq/m^3 in the mines under study. The dose estimate was based on the conversion factor of 5 mSv/WLM on the assumption that the occupancy time in the mines is 4,000–4,500 h/a. Consequently the annual doses for workers were within the range 2.1–7.0 mSv [Q10]. An evaluation of occupational exposure in three underground coal mines in Turkey (Kozlu, Karadon and Üzülmez) indicated average annual effective doses of 4.9 mSv. The total workforce was 12,510 and the collective effective dose was estimated to be 61.5 man Sv [F10]. Evaluation of occupational exposure due to intakes of long-lived radionuclides from the radon decay series by workers in coal mines in Brazil indicated average annual committed effective doses of less than 1 mSv [L17]. In an assessment of occupational radiation exposure carried out in Polish coal mines in 1997, it was estimated that the maximum value of the dose equivalent received by any miner during the period of an entire year of work under such conditions would not exceed 3.5 mSv [I18, S24]. In a survey programme carried out in three underground coal mines in Western Australia employing 297 workers, the estimated average annual effective dose was 2.9 ± 1.5 mSv [H22].

470. An occupational exposure assessment of some 80 coal mines in China was carried out during the period 2002–2004. The results indicated that the average annual dose to the staff of the underground mines is 2.4 mSv, with the largest dose being over 10 mSv [C12]. The effective doses for Chinese coal mine workers seem to have a decreasing trend; the average value was reported as 4.8 mSv for 1999 [T4]. Of the 6 million underground coal miners countrywide, 1 million are working in large coal mines, 1 million in medium-sized coal mines, 4 million in small coal mines and 50,000 in bone-coal mines. Bone-coal is an impure coal that contains much clay or other fine-grained detrital mineral matter; it is hard and compact. On this basis, the collective dose is estimated to be about 14,600 man Sv (table 52). Most of the occupational exposure is due to radon and its progeny [C12].

471. In the Islamic Republic of Iran, there are about 150 underground mines, of which 60% are coal mines and 40% metal mines. To assess the possible presence of high radon levels in these mines, a radon survey programme of non-uranium mines was started in early 2000. The evaluation of occupational exposure in the ten mines gave the following results: 35 workers incurred an average effective dose of 8.3 mSv, and 235 workers an average effective dose of 0.06 mSv in the two manganese mines; 235 workers in the lead mine received an average effective dose of 1.2 mSv; and 8,772 workers in the seven coal mines received an average effective dose of 2 mSv [G9].

472. An assessment was undertaken of occupational exposure in 27 underground non-uranium mines in Western Australia. These mines employed 2,173 workers, which represented nearly 80% of the underground workforce at the time of the survey. The average annual effective dose across all mines was estimated to be 1.4 mSv, ranging from 0.4 mSv for a nickel mine to 4.2 mSv for a coal mine. Radon progeny exposure contributed approximately 70% of the total effective dose [H22].

473. The average annual effective dose to workers in four metal ore mines in Poland was 2.5 mSv (maximum value 9.6 mSv). Annual doses for workers in two lead and zinc mines were estimated at about 4 mSv (maximum value 8.7 mSv), and for workers in two copper mines at about 2.8 mSv (maximum value 7.0 mSv); these doses were also due to radon exposure [I18]. Workers at a commercial underground lead and zinc mine in Ireland have been monitored for radon exposure; 11 workers received annual doses due to radon inhalation in the range 1–6 mSv [C25].

474. The estimated average annual doses received by underground gold mine workers in South Africa were 6.3 mSv in 1997, 4.9 mSv in 1998, 5.4 mSv in 1999 and 7.0 mSv in 2000. The data are presented in table 53. A survey programme carried out in the gold mines during 1993–1994 found that 71% of the dose was due to inhalation of radon gas and its short-lived progeny, 25% due to external gamma exposure and the remaining 4% due to inhalation of dust [I18, W17].

475. An evaluation of the occupational radiation exposure to NORM in surface and underground mining operations in a gold mine in the Ashanti Region of Ghana showed that the annual effective dose is about 0.26 ± 0.11 mSv for surface mining and 1.83 ± 0.56 mSv for the underground mines. The total number of workers was 4,439 [D1].

476. A dose assessment for 45 workers in five different areas of the largest underground phosphate mine in Egypt, the Abu-Tartor phosphate mine, was conducted taking into account measurements of radon, its short-lived decay products, thoron and external dose (using TLDs). The calculated effective dose due to airborne radionuclides was the main contributor to the occupational exposure and exceeded 20 mSv/a, especially at locations in the side tunnels (where levels were higher by a factor of up to 4 because of inadequate ventilation). The average annual effective dose was 11.66 mSv. The mean value of external dose as measured by TLDs was 8.97 mSv/a. These results are presented in table 54. The dose estimate calculated from workplace measurements underestimates the annual dose by around 25% [K11]. The average annual effective dose (due to radon, radon progeny and thoron progeny) in other Egyptian phosphate mines was 70.2 mSv, with a range of 12.2–136.9 mSv

[H31]. More recent evaluation has been conducted in three phosphate mines in Egypt, located in the Eastern Desert about 500 km south of Cairo. The average annual effective doses for workers from the mines, due to inhaled radon progeny, are in the range 107–182 mSv [E3].

477. The estimated annual doses for workers in surface copper mines in Poland were about 1 mSv resulting from internal exposure due to radium and about 0.5 mSv from external exposure [I18]. The exposure of surface workers in gold mines in South Africa is generally very low, except for workers in acid plants, where the radium originating from the pyritic ore can become very highly concentrated during the formation of scales and give rise to substantial external gamma and dust inhalation exposures. A survey of occupational exposure carried out in 1999 in South African mines and mineral processing facilities (other than those associated with gold production) showed that around 98% of the 9,955 workers received doses of less than 5 mSv. The workers with the highest exposures are in copper mining [W17].

478. Another group of exposed workers are those in diamond mines in Africa. Security measures are implemented to reduce diamond thefts. These measures are explicitly authorized through national regulations and cover a large spectrum, from access control to the use of special equipment to prevent the employees having direct contact with the diamonds. Personal searching, including searching by hand and X-ray searching, which is practised in some conditions in some countries, is one of the security measures. Personal searching has two main functions: to recover diamonds that have been concealed with the intention to steal, and to deter and prevent theft. The radiation dose is about 5 μSv per scan in screening workers to detect if they have swallowed or hidden diamonds in their bodies. There is no estimate of the number of workers involved in these diamond mines and of how often they are exposed [I6].

479. A fluorspar mine that operated in St. Lawrence, Newfoundland, Canada, from the early 1930s until 1978 was estimated to have radon progeny concentrations of 2–130 WL. The source of radon was eventually identified as the water that poured into the mines [D3]; the radon itself apparently originated from the host granite. Mechanical ventilation was introduced in all levels of the mine that were still operating, and the radon daughter levels subsequently fell below the suggested limit of 1 WL in 1960 [M31]. The last fluorspar mine was closed in St. Lawrence in 1978. The average annual internal and external effective doses received by workers in the phosphate fertilizer plant were 0.75 mSv and 0.88 mSv, respectively [B39].

480. In most of the extractive and processing industries in Brazil, average annual effective doses were somewhat greater, above 1 mSv [L17]. An evaluation of internal exposure of workers at a thorium purification plant in Brazil showed that the annual effective dose ranged from 0.12 to 1 mSv. In this facility, thorium sulphate is converted in the purification process into concentrated thorium nitrate, $Th(NO_3)_4$, which is then used in gas mantle production [C2]. The average annual effective dose of workers in an electrothermal plant in the Netherlands for producing elemental phosphorus is about 1 mSv [E4]. A radiological survey was conducted and a radiation protection system implemented during the site remediation and decommissioning of an old and abandoned Greek phosphate fertilizer industry. The initial estimate of the effective dose to workers involved in the decontamination process, for a worst-case scenario, was estimated to be up to 9 mSv [K17].

481. Various assessments of annual effective doses received by workers in zircon milling plants have been reported. The results of these assessments are summarized in table 55, from which it would appear that, in most zircon milling operations, workers do not receive annual doses exceeding about 1 mSv. Except for bagging operations, this is likely to be the case even if respiratory protection is not used [I41]. However, the results of the SMOPIE project indicate that zircon milling may give rise to annual doses of between 6 and 20 mSv, in workplaces where protection measures are poor or non-existent [V1].

482. Data from the UNSCEAR Global Survey of Occupational Radiation Exposures on the occupational exposure of workers involved in extractive and processing industries are included in table A-16. For coal mines, only the United Kingdom has reported data on occupational exposure. The workforce consists of 5,000 workers, who represent about 10% of the number reported in the previous period. The average annual effective dose has remained constant at 0.6 mSv. For other mineral mines, five countries have reported data, representing about 1,300 workers. The average effective dose is 1.2 mSv.

483. The level of exposure depends on a number of factors, including the type of mine, the geology and the working conditions, particularly the ventilation. In general, the occupational exposure is distinguished by the type of mine (underground versus above ground). The range of typical values of annual effective dose for underground coal mines is 0.5–4 mSv. The typical average effective dose for coal mining operations is considered to be 2.4 mSv. The range of typical values of annual effective dose for other mineral mining is 1.3–5.0 mSv. The typical average effective dose for other mining operation is considered to be 3.0 mSv. In order to have a rough estimate of the worldwide level of exposure due to the extractive mining industry, it is assumed that the total workforce comprises about 11.5 million workers, that 60% of this workforce (i.e. 6.9 million workers) receive an average annual effective dose of 2.4 mSv, and that 40% of the workforce (i.e. 4.6 million workers) receive an average annual effective dose of 3.0 mSv. This results in an estimate for the annual collective effective dose of about 16,560 man Sv for coal mines and 13,800 man Sv for other mines. This makes a total of some 30,360 man Sv annually for the mining industry as a whole. It has been very difficult to distinguish the level of exposure and the numbers of workers engaged in mining and mineral extraction. In this annex, the

collective dose estimated for workers involved in mineral extraction includes those involved in mineral processing. The level of exposure to radon may be underestimated, since the doses for workers in workplaces where the radon concentration is below 1,000 Bq/m^3 may not be reported. The number of workers, the average effective doses and the collective effective doses are presented in table 57.

484. The UNSCEAR 1988 Report [U7] estimated the collective doses for coal mining as 2,000 man Sv. This was based solely on exposures in mines in the United Kingdom and on the worldwide production of coal. The UNSCEAR 2000 Report [U3] estimated the collective dose as about 2,600 man Sv, which was about 16% of the current estimate of 16,560 man Sv. For non-coal mines, the collective dose estimate has also increased considerably. The UNSCEAR 2000 Report [U3] estimated the collective dose as about 2,000 man Sv, which is about 14% of the current estimate of 13,800 man Sv. The overall estimate for mining activities is 30,360 man Sv, which is about seven times higher than the previous estimate [U3].

3. Gas and oil extraction

485. Naturally occurring radioactive material (NORM) found in the earth's crust, largely in the form of ^{226}Ra and ^{228}Ra and their associated radionuclides, is brought to the surface during gas and oil production processes. The NORM represents a potential internal radiation exposure hazard to both workers and members of the public through the inhalation and ingestion of radionuclides. In addition, a gamma exposure rate higher than normal background has been observed in the oil and gas industry.

486. The mixed stream of oil, gas and water associated with the production process also carries the noble gas ^{222}Rn, generated in the reservoir rock through the decay of ^{226}Ra. This radioactive gas emanating from the production zone travels with the gas/water stream and then preferentially follows the dry export gases. As a consequence, equipment from gas treatment and transport facilities may accumulate ^{210}Pb formed from the short-lived progeny of ^{222}Rn, which plate out on to the inner surfaces of gas lines. These ^{210}Pb deposits are also encountered in liquefied natural gas processing plants [G7].

487. NORM in the oil and gas industry has the potential to give rise to external exposure during production owing to the accumulation of gamma-emitting radionuclides. Moreover, it can give rise to internal exposure to workers and other persons through the inhalation or ingestion of radionuclides, particularly during maintenance, the transport of waste and contaminated equipment, the decontamination of equipment and the processing of waste. The short-lived progeny of the radium isotopes, in particular of ^{226}Ra, emit gamma radiation capable of penetrating the walls of internally contaminated pipes and vessels. Therefore the deposition of contaminated scales and sludge inside these components produces enhanced dose rates outside them as well. The values depend on the amount and activity concentrations of radionuclides present inside the components and the degree of shielding provided by the pipe or vessel walls. Maximum dose rates usually range up to a few microsieverts per hour, but in a few cases dose rates of up to 100 μSv/h (about 1,000 times greater than the normal background values due to cosmic and terrestrial radiation) have been reported outside production equipment [M14, T2, W9].

488. At the Omar oilfield in Syria, the highest equivalent dose rates were 30 μSv/h on the surface of the well-head and 25 μSv/h on the surface of some piping containing scale deposits, especially in valve and bend areas. In the Gulf of Suez oilfield in Egypt, the maximum equivalent dose rate measured at the surfaces of separator tanks and piping, and due to scale precipitate, was 33 μSv/h [A9]. Dose rates observed in oil production and processing facilities vary from 0.1 μSv/h to 300 μSv/h [I23].

489. The IAEA has published information concerning concentrations of NORM in oil, gas and by-products that may result in occupational radiation exposure. The concentrations of ^{226}Ra, ^{228}Ra and ^{224}Ra in scales and sludge range from less than 0.1 Bq/g to 15,000 Bq/g. The activity concentrations of radium isotopes are lower in sludge than in scales. The opposite applies to ^{210}Pb, which usually has a relatively low concentration in hard scales but may reach a concentration of over 1,000 Bq/g in lead deposits and sludge. Although thorium isotopes are not mobilized from the reservoir, the decay product ^{228}Th grows in from the decay of ^{228}Ra after deposition of the latter. As a result, when scales containing ^{228}Ra age, the concentration of ^{228}Th increases to about 1.5 times the concentration of ^{228}Ra still present [I23].

490. An assessment of the occupational exposure *t* due to petroleum pipe scales has been performed for three oilfields. Four radiation exposure pathways were investigated: inhalation of pipe scale dust generated during pipe rattling; incidental ingestion of the pipe scale dust; external exposure resulting from uncleaned pipes; and external exposure resulting from pipe scale dispersed on the ground. The estimated annual effective dose for the operator and the assistant was 0.11–0.45 mSv for inhalation and 0.02–0.1 mSv for sporadic ingestion. The annual effective dose due to external exposure from uncleaned pipes ranged from 0 to 0.28 mSv. The annual effective dose due to external exposure from pipe scale dispersed on the ground was estimated to be 2.8 mSv for the operator and 4.1 mSv for the assistant [H5].

491. According to an estimate based on assuming the inhalation of 5 μm AMAD (activity median aerodynamic diameter) particles incorporating ^{226}Ra (with its complete decay chain in equilibrium), ^{228}Ra and ^{224}Ra (also with its complete decay chain in equilibrium), each at a concentration of 10 Bq/g, a committed effective dose per unit intake of about 0.1–1 mSv/g would be delivered. The exact value depends on the extent of ingrowth of ^{228}Th from the decay of ^{228}Ra and on the lung absorption types assumed. For 1 μm AMAD

particles, the committed effective dose per unit intake would be 25–30% higher [I23].

492. Available data from the UNSCEAR Global Survey of Occupational Radiation Exposures for gas and oil extraction are included in table A-16. The data have been presented for only two countries. The total number of monitored workers was 500 for the period 1995–1999 and 600 for 2000–2002, and the average effective dose was 1.3 mSv for both periods. It is difficult to estimate the collective dose for this practice since the total number of workers exposed to ionizing radiation is not known.

4. Radon exposure in workplaces other than mines

493. The levels of radon in workplaces are exceptionally variable, and high doses to workers can arise in places other than uranium mines. Regulatory authorities have recognized the importance of controlling radon exposure in workplaces other than mines. The European Guideline 96/29/Euratom [E10], which formulated basic safety standards for the protection of the health of workers and members of the general public against the hazards of ionizing radiation, included consideration of areas where the presence of natural radiation sources would increase exposures to employees or members of the public to levels that could not be ignored from the standpoint of radiation protection. ICRP Publication 65 [I48, I61] indicated a planning value in the range 500–1,500 Bq/m^3, above which radiation protection measures are required; orientation values are available for application to health protection.

494. The radiation protection regulations applied in Switzerland since the promulgation of 1994/SSS-94 [S33] established a radon concentration limit of 3,000 Bq/m^3 for industrial areas. Orientation values of 200 Bq/m^3 and 400 Bq/m^3 were indicated for new buildings and for the renovation of buildings, respectively. These workplaces are varied in nature. They include industries (food industries, breweries, laundries, etc.), waterworks, shops, public buildings and offices, schools, subways, spas, caves and closed mines open to visitors, underground restaurants and shopping centres, tunnels (construction and maintenance) and sewage facilities [I21, S39, S41].

495. An occupational exposure survey in over 500 of the 2,600 water supply facilities in Bavaria showed that, in all geological regions, exposure levels giving rise to over 6 mSv/a can occur. About 2% of the staff is subjected to exposure levels that give rise to over 20 mSv/a [S40, T9, T10]. A survey of occupational exposure was conducted in ten drinking water supply plants in Slovenia. The annual doses were found to be below 0.5 mSv at six of the workplaces and in the range 0.6–3.0 mSv at the other four [V16].

496. Occupational exposure in radon therapy rooms is related to the different treatment procedures, which affect the temporal variation of radon and its progeny. An evaluation of occupational exposure due to radon and its progeny in the treatment facilities of the radon spa Bad Gastein in Austria produced different dose ranges for each of the four treatment rooms monitored. The estimated annual effective doses were 9.4–32 mSv, 1.8–2.4 mSv, 1.3–1.7 mSv and 0.2–0.3 mSv [L7]. The annual individual effective doses to the employees of a therapeutic dry carbon dioxide spa in Hungary, due to inhalation of ^{222}Rn, ranged from 0.9 to 4.2 mSv. The highest dose to a staff member was received by an attendant who spent much of his time in the treatment room watching over the patients in the "pit" [C30]. The results of the dose assessment for a therapeutic cave in Hungary showed that staff received doses of up to 20 mSv/a when working 4 hours per day in the cave [K6]. Annual effective doses of between 1 and 44 mSv were estimated for workers in Spanish spas [S29]. Bath attendants were the working group subject to the highest doses. In Slovenia, a dose assessment was performed in five spas; the radon concentration in indoor air rarely exceeded 200 Bq/m^3 [V13].

497. In Slovenia, there are more than 3,000 caves located in the Karst regions. Some 50 professional guides and other workers are employed in the Postojna and Skocijanske caves, and many volunteers from local cave associations work or serve as guides for visitors in about 20 other caves. Annual doses, estimated on the basis of various lung models, ranged from 10 to 85 mSv [J7]. A survey carried out in 2002 of occupational exposure in three Irish caves showed that 13 workers received annual doses due to radon inhalation in the range 1–6 mSv, and one worker received an estimated annual dose of 12 mSv [C25]. A dose assessment was carried out in 2004–2005 in the Lantian Xishui karst cave of Shaanxi, China. The average annual effective dose to tour guides was found to vary between 1.2 mSv and 4.9 mSv [L23].

498. A radiation survey of seven archaeological sites inside Egyptian pyramids or tombs, conducted in the Saggara area, obtained measurements of radon (^{222}Rn) and its short-lived decay products, thoron (^{220}Rn) progeny and gamma radiation. In seven of the pyramids and tombs, workers could receive annual doses ranging from 2 to 13 mSv; in the others, annual doses were less than 1 mSv [B26]. The dose assessment for the workers at two archaeological sites in Alexandria, Egypt, has shown that the effective doses are in the range 0.05–5 mSv/a at both sites [H2]. The estimated average annual effective dose to tour guides at the great pyramid of Cheops was 0.05 mSv, and estimates for the pyramid guards varied from 0.19 to 0.36 mSv [H1].

499. A programme of radon measurements in Irish schools has been conducted since 1998. A total of 45,000 individual radon measurements were made in 3,444 primary and post-primary schools. The average radon concentration was 93 Bq/m^3, comparable with the 89 Bq/m^3 observed for homes; the highest concentration measured was 4,948 Bq/m^3. In 74% of the schools, no classrooms had radon concentrations of greater than 200 Bq/m^3, while in 9% of the schools, the radon concentration in at least one classroom exceeded 400 Bq/m^3. A total of 591 schools (17% of those

measured) had radon concentrations of between 200 and 400 Bq/m^3. A total of 898 schools (26% of those measured) will require some degree of remediation to reduce indoor radon concentrations [C25]. The radiation survey performed in 25 classrooms in the capital city of Kuwait between September 2003 and March 2004 showed that the annual dose was about 1 mSv [M1]. In a radon survey in a school with elevated levels of radon in Slovenia, the annual effective doses received by the staff were estimated to range from 1.3 to 12.6 mSv [V15]. Another radiation survey, in schools on the territory of an abandoned uranium mine in Slovenia, found that the annual doses for the staff ranged from 0.07 to 0.27 mSv [V14]. An extensive radon survey was performed in 890 schools in Slovenia, and radon concentrations with an arithmetic mean of 168 Bq/m^3 and a geometric mean of 82 Bq/m^3 were found. In 67% of the schools, indoor radon concentrations were below 100 Bq/m^3, while in 8.7% of them the concentration exceeded 400 Bq/m^3. The average value of the gamma dose rate measurements was 102 nGy/h and the geometric mean was 95 nGy/h [V11, V12].

500. The average annual effective dose to the workers in 94 offices in Hong Kong has been estimated to be 0.35 mSv [Y3]. In the United Kingdom, a study was undertaken throughout British Telecom underground workplaces during 1993–1994 to assess occupational exposure due to radon. The study concluded that no British Telecom staff received an annual radiation dose of greater than 5 mSv [W13]. In Venezuela (Bolivarian Republic of), the average effective dose received by the employees of the Caracas subway system has been estimated as about 1 mSv/a [L9] A radiation survey in 201 rooms of 26 major hospitals in Slovenia gave an estimate of the annual effective doses for 966 staff (94.2%) of less than 1 mSv, but for 10 workers the doses were between 2.1 and 7.3 mSv [V17].

501. Available data from the UNSCEAR Global Survey of Occupational Radiation Exposures for radon in workplaces other than mines are included in the last part of table A-16. Five countries have reported data for the period 2000–2002. These data show considerable variation for the average effective dose, from 0.7 to 5 mSv. Germany has reported separate data for spas, waterworks and tourist caves. The average effective dose for people working in spas, 4 mSv, is twice that in the other workplaces, 2 mSv, as shown in table 56.

502. Elevated levels of radon have been found in a number of countries, but the levels of exposure vary considerably according to the workplace. So far the UNSCEAR reports have performed only crude estimates of the worldwide levels of exposure, owing to a lack of information. Although the number of data available for the last two periods has increased compared with the previous periods, the sample sizes are still very small and the levels of exposure depend on factors that vary from country to country, such as geology, building materials and regulatory regimes. There are clearly very few data on which to base an accurate estimate of worldwide exposure. Since the scenario of exposure throughout the world has not changed dramatically since the UNSCEAR 2000 Report, the number of exposed workers is estimated as 1.250 million, the collective effective dose as about 6,000 man Sv and the average effective dose as 4.8 mSv (table 57). The level of exposure is the same as estimated in the UNSCEAR 2000 Report [U3]. Clearly this estimate is very crude.

5. Conclusions on occupational exposure to natural sources of radiation

503. After the implementation of the International Basic Safety Standards [I7] and subsequently the implementation of the European Union standards for the protection of workers exposed to natural radiation (European Union Directive 96/29/Euratom) [E10], data on levels of occupational exposure to natural sources of radiation have become available, mainly in the European Union countries. Other qualifying data are needed on specific issues for each category of exposure in order to be able to derive an accurate estimate for the worldwide average levels of exposure to natural sources of radiation. The highest level of occupational exposure comes from exposure to natural sources of radiation.

504. Data have indicated that aircrew are one of the most highly exposed occupational groups. In Germany, the collective dose to this group, 60 man Sv, contributes more than 50% of the total collective dose to all workers in the country. The estimated worldwide collective effective dose to aircrew is about 900 man Sv. This value is about the same as that estimated in the UNSCEAR 2000 Report, 800 man Sv [U3].

505. Work activities with materials containing NORM can involve significant exposure of workers through internal contamination by inhalation. However, there can be considerable differences in workplace conditions, the radionuclides involved and the physical and chemical matrices in which the radionuclides are incorporated.

506. The level of exposure in mines depends on a number of factors, including the type of mine, the geology and the working conditions, particularly the ventilation. The UNSCEAR 1988 Report [U7] estimated the global collective dose for coal mining as 2,000 man Sv. The UNSCEAR 2000 Report [U3] estimated the collective dose as about 2,600 man Sv, which is about 16% of the present estimate of 16,560 man Sv. For coal mines, the estimated number of workers is 6.9 million and the average effective dose is 2.4 mSv. The increase is due to taking into consideration the contribution of the coal miners in China. The current estimate of the exposure levels for coal miners seems to be more realistic than the previous ones, since it is based on data obtained from a comprehensive survey performed in China, which represents the great majority of the global workforce. On the basis of the survey programme carried out in China, the level of exposure appears to be declining, since the annual effective dose fell from 4.8 mSv in 1999 to 2.4 mSv in 2000–2002 [C12, T4]. For non-coal mines, the collective dose estimate has also increased considerably.

The UNSCEAR 2000 Report [U3] estimated the collective dose as about 2,000 man Sv, which is about 14% of the current estimate of 13,800 man Sv. The estimated number of workers in non-coal mines is about 4.6 million, and the average effective dose is 3.0 mSv. However, for non-coal miners the worldwide estimate is still only rough, since the data need to be qualified with regard to their completeness, in particular for the number of workers engaged in underground and above-ground mines. The overall estimate for mining activities is 30,360 man Sv, which is about seven times higher than the previous estimate [U3].

507. The SMOPIE project, which dealt with occupational internal exposures from practices and work activities in NORM industries in European countries, covered a broad variety of practical issues, including: the generation of and exposure to dust; whether the exposure is continuous or discontinuous; whether the exposure is worker-induced or process-induced; and the variation of doses between workers. Several studies have been reviewed, but they do not provide the information required for a scientifically sound evaluation of the problem. The results of the project have revealed that there still is a severe lack of information on the number of exposed workers in NORM industries and on the associated occupational doses. The number of 85,000 exposed workers, as derived in this project, warrants more research. The largest group of exposed workers (70,000) appears to be welders using thoriated welding electrodes. The available data suggest that the grinding of welding rods may give rise to annual doses of between 6 and 20 mSv [S4, V1]. There is some evidence that alternative (non-radioactive) welding rods are increasingly being used. This means that the number of exposed workers should decrease in the future. A survey programme in Denmark has shown that the annual committed effective dose from the inhalation of ^{232}Th, ^{230}Th, ^{228}Th and ^{228}Ra, for a full-time TIG (tungsten inert gas) welder, is below 0.3 mSv in a realistic case and around 1 mSv or lower with conservative assumptions. The contribution from grinding electrodes was lower, 0.010 mSv or less [G2]. Again, precise details on this trend were not available.

508. According to the SMOPIE project, the second largest group of exposed workers (10,000) are those trading or using phosphate fertilizers (The data originate from only one country.). The results indicate that, like the grinding of thoriated welding rods, zircon milling may also give rise to annual doses of between 6 and 20 mSv in workplaces where protection measures are poor or non-existent. Rare earth processing may even give rise to annual doses of greater than 20 mSv. In both industries, the number of exposed workers is small [V1].

509. The results of the occupational exposure survey performed in nine European Union countries from 1996 to 2000 have shown that the average annual effective dose declined from 6 to 3 mSv during that period. The annual collective dose fell from 70 to 39 man Sv; therefore the mean value may be influenced by the increasing number of monitored workers. The reduction of 71% in the number of workers receiving annual doses of over 20 mSv is the largest for all work sectors. There was a substantial change in the dose distribution towards lower values in almost all dose bands. However, substantial differences exist between the countries where monitoring was undertaken. There are some uncertainties in this evaluation, since the registered doses may include uranium miners as well as non-uranium miners or workers in tourist caves and at drinking water facilities, i.e. they include external exposures as well as doses from radon inhalation. The recommendations of ICRP Publication 65 [I48] changed the dose calculation substantially by introducing conversion factors and detriment coefficients, as a consequence of which the values of the calculated doses fell considerably. However, the declining values of the annual doses may also be a result of modified work management and workplace conditions [F15]. In conclusion, a declining level in reported occupational exposures to natural sources of radiation in European countries has been seen, although substantial differences exist between the countries where monitoring is undertaken [F15].

510. Elevated levels of radon have been found in a number of countries, but the levels of exposure vary considerably depending on the workplace. The level of exposure to radon may be underreported, since the doses for workers in workplaces where the radon concentration is below 1,000 Bq/m^3 may not be reported. So far the UNSCEAR reports have performed only crude estimates of the worldwide levels of exposure, owing to a lack of information. Although the number of data available for the last two assessment periods has increased compared with the previous periods, the sample sizes are still very small and the levels of exposure depend on many factors that vary from country to country, such as geology, building materials and regulatory regimes. There are clearly very few data on which to base an accurate estimate of worldwide exposure. Since the scenario of exposure throughout the world has not changed dramatically since the UNSCEAR 2000 Report, the same value for the worldwide annual collective effective dose of 6,000 man Sv is assumed. As in the UNSCEAR 2000 Report [U3], the number of workers is estimated to be 1.250 million and the average effective dose to be 4.8 mSv. These estimates are clearly very crude.

511. The worldwide level of exposure for workers exposed to natural sources of radiation has increased considerably compared with the UNSCEAR 2000 Report [U3]. The estimated number of workers is about 13 million. The estimated average effective dose is 2.9 mSv and the estimated collective effective dose is 37,260 man Sv.

C. Man-made sources for peaceful purposes

1. Nuclear power production

512. A significant source of occupational exposure is the operation of nuclear reactors to generate electrical energy. This involves a complex cycle of activities, including the

mining and milling of uranium, uranium enrichment, fuel fabrication, reactor operation, fuel reprocessing, waste handling and disposal, and research and development activities. Exposures arising from this practice were discussed and quantified in the UNSCEAR 1972 [U11], 1977 [U10], 1982 [U9], 1988 [U7], 1993 [U6] and 2000 [U3] Reports, with comprehensive treatment in the UNSCEAR 1977, 1982 and 2000 Reports. In comparison with many other sources of exposure, this practice is well documented, and considerable quantities of data on occupational dose distributions are available, in particular for reactor operation. This annex considers occupational exposure arising at each main stage of the fuel cycle. Because the final stage—treatment and disposal of the main solid wastes—is not yet sufficiently developed to warrant a detailed examination of potential exposures, it is given only very limited consideration. However, for the period under consideration, occupational exposures due to waste disposal are not expected to add a significant amount to the collective exposure of workers to radiation due to the other stages in the fuel cycle.

513. Each stage in the fuel cycle involves different types of workers and work activities. In some cases, for example for reactor operation, the data are well segregated, while in others the available data span several activities, e.g. uranium mining and milling. Where the data span a number of activities, this is noted in footnotes to the tables. The data on occupational exposures for each of the activities are derived primarily from the UNSCEAR Global Survey of Occupational Radiation Exposures [U3, U6, U7, U9, U10] but also from other sources, particularly the joint OECD/NEA and IAEA Information System on Occupational Exposure (ISOE) [O14, O19, O20], which serves as a main source of occupational exposure data for reactor operations in the period 1995–2002.

514. For each stage of the fuel cycle, this annex provides estimates of the magnitude of and temporal trends in the annual collective and per caput effective doses, the numbers of monitored workers and the "distribution ratios". The collective doses are also expressed in normalized terms, i.e. per unit practice relevant to the particular stage of the cycle. For uranium mining and milling, fuel enrichment, fuel fabrication and fuel reprocessing, the normalization is initially presented in terms of unit mass of uranium or fuel produced or processed. An alternative way to normalize is in terms of the equivalent amount of energy that can be (or has been) generated by the fabricated (or enriched) fuel. The bases for the normalizations, i.e. the amounts of mined uranium, the separation work during enrichment and the amount of fuel required to generate a unit of electrical energy in various reactor types, are given in section II.C of this annex. For reactors, the data may be normalized in several ways, depending on how they are to be used. In this annex, normalized collective doses are given for each reactor type and per unit electrical energy generated.

515. To allow proper comparison between the doses arising at different stages of the fuel cycle, all the data are ultimately presented in the same normalized form, in terms of the electrical energy generated (or the amount of uranium mined or of fuel fabricated or reprocessed, corresponding to a unit of energy subsequently generated in the reactor), which is the principal measure of output of the nuclear power industry. This form of normalization is both valid and useful when treating data averaged over a large number of facilities or over a long time. It can, however, be misleading when applied to data for a single facility for a short time period. This is because a large fraction of the total occupational exposure at a facility arises during periodic maintenance operations, when the plant is shut down and not in production. Such difficulties are, however, largely circumvented in this annex, since the data are presented in an aggregated form for individual countries and are averaged over five-year periods.

516. Various national authorities or institutions have used different methods to measure, record and report the occupational data included in this annex. The main features of the method used by each country that responded to the UNSCEAR Global Survey of Occupational Radiation Exposures are summarized in table A-15. Data collected under ISOE are provided by participants according to standardized reporting formats, although the details requested have increased over time, and not all countries report to the same level of detail. Additionally, the data provided under ISOE are based on operational data collected from the participating utilities, and may differ slightly from official dose records. The reported collective doses and the collective dose distribution ratios are largely insensitive to the differences identified in table A-15, so these quantities can generally be compared without further qualification. The average doses to monitored workers and the number distribution ratios are, however, sensitive to the decisions and practices concerning which workers in a particular workforce are to be monitored. Differences in these areas could not be discerned from responses to the UNSCEAR Global Survey of Occupational Radiation Exposures, and they therefore cannot be discerned from table A-15. However, because the monitoring of workers in the nuclear power industry is in general fairly comprehensive, comparisons of the average individual doses (and number distribution ratios) reported here are judged to be broadly valid. Nonetheless, it must be recognized that differences in monitoring and reporting practices do exist, and they may, in particular cases, affect the validity of comparisons among reported data. As mentioned before, the criteria applied in different countries to select workers who should be monitored differ considerably. Some countries monitor only the exposed workers, while others also include the non-exposed workers in their individual monitoring programme for various reasons.

(a) Uranium mining and milling

517. Most natural uranium is mined for energy production in fission reactors, but it is also used in nuclear research reactors and in military activities. Commercial uranium use is primarily determined by the fuel consumption requirements

of power reactors and continues to increase steadily, while the requirements for research reactors remain modest by comparison.

518. The mining of uranium is similar to that of any other material. It mainly involves underground or open-pit techniques to remove uranium ore from the ground, followed by ore processing, usually performed at a location relatively close to the mine. The milling process involves the crushing and grinding of raw ores, followed by chemical leaching, the separation of uranium from the leachate and precipitation of yellowcake [K14], and the drying and packaging of the final product for shipment.

519. Uranium mining has been conducted in 24 countries (see table 14 for annual uranium production worldwide and section II.C of this annex) over the period 1998–2003. This practice has ended in some countries. Between 1990 and 1997, 34 countries were involved in uranium mining, and over the whole nuclear era, some 37 countries [U3]. The major producer is Canada, which is responsible for about 30% of the world production, followed by Australia with about 14%, and Niger with about 10%. About 93% of the world's production comes from only ten countries: Australia, Canada, Kazakhstan, Namibia, Niger, the Russian Federation, South Africa, Ukraine, United States and Uzbekistan.

520. In the mining and milling of uranium ores, the workers incur both internal and external radiation exposures. Mining operations such as drilling, blasting, loose-dressing, mucking, crushing, boulder-breaking, loading and dumping, etc., generate ore dusts of different particle sizes, which become dispersed in the mine environment and give rise to an inhalation hazard. Concentrations of these ore dusts are quite variable with time and location. Extremely high values can be reached during blasting and ore dumping. In general, these workplaces are very dusty, and consequently there is a potential risk for inhalation of aerosol particles containing radionuclides from the ^{238}U decay chain. The internal dose depends on workplace conditions, which vary considerably according to the type of mine (underground or above ground), the ore grade, the airborne concentrations of radioactive particles (which vary depending on the type of mining operation and the quality of ventilation) and the particle size distribution. In underground mines, the main source of internal exposure is likely to be radon and its decay products. Because of the confined space underground and practical limitations to the degree of ventilation that can be achieved, the total internal exposure is of greater importance in underground mines than in open-pit mines. In open-pit mines, the inhalation of radioactive ore dusts is generally the largest source of internal exposure, although the doses tend to be low. Higher doses resulting from this source would be expected in the milling of the ores and the production of yellowcake. Internal exposure makes by far the greatest contribution to the total exposures resulting from underground mining.

521. Exposure data for the mining and the milling of uranium ores from the UNSCEAR Global Survey of Occupational Radiation Exposures for 1995–2002 are given in tables A-17 and A-18, respectively, and trends for the six periods 1975–1979, 1980–1984, 1985–1989, 1990–1994, 1995–1999 and 2000–2002 are given in figure XXXVIII.

522. Over the four previous five-year periods (1975–1994), the average annual amounts of uranium mined worldwide were 52, 64, 59 and 39 kt. For the periods 1995–1999 and 2000–2002, the average annual amounts mined were 34 kt. This represents a reasonably constant level of production for the first three periods and a reduction by about one third for the last three periods. The average annual amount of uranium mined remained constant over the last three periods.

523. Germany has ceased mining operations; its reported doses relate to the decommissioning of mines. Other countries, e.g. France and Spain, are in the same situation. Still other countries, e.g. Argentina, Belgium, Gabon and Hungary, have completely stopped their uranium production in the last several years (see table 14).

524. The estimate of worldwide levels of exposure resulting from uranium mining has been derived by scaling up to the total world uranium production from the 36% of production for which data were reported. For the reported data, Canada dominates, accounting for about 30% of the world uranium production. On this basis, the average annual number of monitored workers worldwide has decreased dramatically over time: 240,000, 310,000, 260,000, 69,000 in the first four periods (1975–1979, 1980–1984, 1985–1989 and 1990–1994), compared with 22,000 and 12,000 in the last two periods (1995–1999 and 2000–2002). These reductions by a factor of 3 and 6 in the last two periods are also seen in the values for average annual collective effective doses. For the first four periods the worldwide estimates were 1,300, 1,600, 1,100 and 310 man Sv, but for 1995–1999 and 2000–2002 the values fell to 85 and 22 man Sv, respectively. Similarly, the average collective dose per unit mass of uranium extracted was 26, 23, 20 and 8 man Sv/kt for the first four periods and declined to 2 and 1 man Sv/kt for 1995–1999 and 2000–2002, respectively. However, the estimated average annual effective doses have been high over the years, even though they started to decrease in the last two periods: they decreased from 4.5 mSv in 1990–1994 to 3.9 mSv in 1995–1999 and to 1.9 mSv in 2000–2002. The average effective dose for measurably exposed workers has decreased significantly as well. The data are consistent with a worldwide reduction in underground mining activity coupled with more efficient mining operations. The trends are presented in table 58 and are represented graphically in figure XXXVIII.

525. In order to evaluate the occupational exposure in underground and above-ground mines, a new questionnaire was distributed requesting the data to be provided separately. Canada and Germany have reported data separately for above-ground and underground mines. The data are presented in table 59. The effective doses were in the range 0.3–1.3 mSv for above-ground mines and 1.0–3.1 mSv for

underground mines. Effective doses for the workers in the underground mines are at least twice as high as those in the above-ground mines. The data reported by Germany for underground mines are related to the decommissioning of mining facilities. The doses reported by Canada show a decreasing number of monitored workers and decreasing collective dose and average effective dose for underground miners. The major reason for the reduction in the level of occupational exposure in Canada is that uranium mining moved from the conventional cut-and-fill method used to mine ore grades of around 0.1% U in northern Ontario to the more advanced, non-entry type of method used to mine the higher-grade ores (some exceeding 20% U) in northern Saskatchewan. These non-entry mining methods significantly reduced gamma radiation exposures and greatly restricted exposure to radon progeny and uranium ore dust.

526. The contribution of internal and external exposure to the total effective dose has been analysed in this annex on the basis of data provided by Canada, the Czech Republic and Germany for each type of mine. The percentage dose contributions from radon and ore dust inhalation and from external exposure are given in table 60. The contribution of each source varies according to the type of mine and the ore grade. However, internal exposure is the main contributor to the total effective dose, independent of the type of mine, and its overall contribution is about 70%.

527. According to the Canadian Occupational Radiation Exposures reports [H9, H10, H11, H12, H13, H14], radiation exposure is significantly higher for underground mining workers than for surface mining workers. It also differs considerably according to job function. The contribution of radon exposure to the total effective dose is about 60%, independent of the type of mine. As shown in table 61, the annual effective dose to the more exposed miner job category in Canada, averaged over the period 1995–2001, fell from 11 mSv to 2 mSv for underground mines and rose from 1 mSv to 2 mSv for above-ground mines.

528. For the period 1996–2000, the average annual doses received by workers at three underground uranium mines in India were around 8 mSv. The main contribution to the effective dose came from inhalation of ^{222}Rn and its short-lived progeny [K10].

529. The assessment of exposure of miners to the long-lived α-emitting radionuclides associated with respirable ore dusts in the Jaduguda uranium mine in India, where the U_3O_8 concentration is less than 1%, has shown that the inhalation of ore particles has contributed only about 5% of the annual effective dose limit, indicating that in this mine it is not a significant source of exposure [J3]. At ore grades of up to about 3% U_3O_8, limitation of airborne silica will usually place a stricter constraint upon dust concentration than does radioactivity. However, at ore grades in excess of 3% U_3O_8 and when the ore is not high in silica, radiation exposure resulting from inhalation of ore dust could become important.

530. Data on exposure of workers due to uranium milling are presented in table A-18. The Committee assumes that the amount of uranium milled is equal to the amount mined. The estimated worldwide level of exposure has decreased over the six periods: *(a)* the average annual number of monitored workers was 3,000 for the periods 1995–1999 and 2000–2002, which is substantially fewer than in the previous four periods: 12,000, 23,000, 18,000 and 6,000; *(b)* the average annual collective effective dose was 4 man Sv and 3 man Sv for 1995–1999 and 2000–2002, respectively, compared with 124, 117, 116 and 20 man Sv for the previous four periods; *(c)* the average annual effective dose was 1.6 mSv and 1.1 mSv for 1995–1999 and 2000–2002, respectively, compared with 10.1, 5.1, 6.3 and 3.3 mSv for the previous four periods. The data are presented in table 62 and figure XXXIX.

(b) Uranium conversion and enrichment

531. Uranium conversion is the process by which UO_2, which is the chemical form of uranium used in most commercial reactors, is produced for the fabrication of reactor fuel. Some reactors use fuel slightly enriched in ^{235}U (generally about 3% enrichment, in contrast to natural uranium, which contains about 0.7% ^{235}U). The U_3O_8 from the milling process is converted to UO_2 by a reduction reaction with H_2. The UO_2 is converted to UF_4 by the addition of hydrofluoric acid (HF) and then to UF_6 using fluorine (F_2). The gaseous product, uranium hexafluoride (UF_6), is then enriched in ^{235}U. Most of this is performed by the gas diffusion process, but gas centrifuge techniques are being used increasingly. Once the enrichment process has been completed, the UF_6 gas is reconverted into UO_2 for fuel fabrication [U3].

532. In 2003 there were 29 uranium conversion/recovery facilities and 21 uranium enrichment facilities in operation. The enrichment capacity of these facilities and a few other small producers is presented in section II.C of this annex. The greater part of the enrichment services came from five suppliers: the United States Department of Energy, Eurodif (France), Techsnabexport (Russian Federation), Urenco (Germany, Netherlands and United Kingdom) and China [X1]. Most thermal reactors use enriched uranium with typically a 3% level of enrichment. Four types of uranium fuel will be considered: unenriched metal fuel, used in Magnox reactors; low-enriched oxide fuel, used in AGRs and LWRs; unenriched metal fuel, used in HWRs; and mixed oxide fuel, used in FBRs. Mixed oxide (uranium–plutonium) fuels are increasingly being developed for use in LWRs.

533. Exposure data for this practice are given in table A-19. The average annual number of monitored workers increased from 12,600 in 1990–1994 to about 18,000 in 2000–2002. The average annual collective dose has increased from 1.28 to 1.70 man Sv. The average annual effective dose to monitored workers was low, 0.1 mSv, in 1995–2002, and has not changed since 1985–1989. The absence of data from the Russian Federation would suggest that these figures are

underestimates. Even taking this into account, the individual and collective doses arising from enrichment are low. The trends in this practice are presented in table 64 and figure XL.

534. Occupational exposure occurs during the enrichment and conversion stages of the fuel cycle. External radiation exposure is more important than internal radiation exposure, but workers may be exposed to internal radiation, particularly during maintenance work or in the event of leaks. The workers may be exposed to UF_6, classified as a soluble compound and assigned as Type F for lung retention, according to the ICRP [I51, I57]. In these situations, the occupational exposure to daily intakes of these uranium compounds of any isotopic composition would be limited by considerations of chemical toxicity rather than radiation dose [I55, S40]. A new questionnaire was distributed to Member States to obtain information about the contribution of internal exposure to the total effective dose. Data from China show that 64% of the dose is due to external exposure. The contribution of each source varies according to the level of exposure. The data provided by China show that, for effective doses lower than 1 mSv, the contributions of internal and external exposure are about the same. For effective doses higher than 1 mSv (1–5 mSv), the contribution of internal and external exposure is about 17% and 83%, respectively.

(c) Fuel fabrication

535. The characteristics of fuels that are relevant here are the degree of enrichment and the form, either metallic or oxide. The majority of reactors use low-enriched fuel (typically 3–5% ^{235}U). The main exceptions are the gas-cooled Magnox reactors and the HWRs, which use natural uranium. Some older research reactors use high-enriched uranium (up to 98%); however, for security reasons this material is being used ever less frequently. The principal source of exposure during fuel fabrication is uranium (after milling, enrichment and conversion, most decay products have been removed).

536. Exposure data for fuel fabrication are given in table A-20. The average annual number of monitored workers has been reasonably constant over the six periods at about 20,000 but with a small peak of 28,000 in the 1985–1989 period. The worldwide average annual number of measurably exposed workers has been approximately 10,000, about half the number of monitored workers. The estimated average annual collective dose showed a decline, from 36 to 21 man Sv, between the first two five-year periods, showed little change over the next two periods, with the value for 1990–1994 being approximately 22 man Sv, and then increased to about 30 man Sv for the last two periods. The average annual effective dose to monitored workers showed an initial decline, from 1.8 to 1.0 mSv, between the first two periods, and the value for 1990–1994, 1.0 mSv, is very similar to that for 1980–1984. For the last two periods the average effective dose increased by about 60%. The trends in occupational exposure are presented in table 65 and figure XLI.

537. The increase in the average effective dose may have two possible reasons: the inclusion of new countries that contributed higher levels of exposure in these last two periods, and the fact that some countries began to include the dose due to internal exposure in their dose records. There are two main sources of exposure in the fabrication of nuclear fuels: external exposure to gamma radiation and internal exposure resulting from the inhalation of airborne material. China has provided information that the doses below 1 mSv are entirely due to external exposure. However, for the doses above 1 mSv, there is an important contribution from internal exposure (between 30% and 80%). According to an NRC report on fuel fabrication facilities, internal exposure contributes most of the total effective dose, up to about 99% of the total dose [U29, U30, U31, U32, U33, U34, U36, U37]. However, the internal dose component depends on the type of nuclear fuel. The occupational exposure in the production of nuclear fuel is expected to be lower for fuel that involves only natural uranium than for fuels that involve enriched uranium or plutonium. In conclusion, the type of dose that is recorded in the national databases can be a source of discrepancy among countries. Some countries record only the doses from external exposure and others record the doses due to both internal and external exposure. Some countries also include in their individual monitoring programme workers who do not work in controlled areas. The variation in types of nuclear fuel also influences the comparison of doses between countries.

(d) Reactor operation

538. The types of reactor used for electrical energy generation are characterized by their coolant system and moderator: light-water-moderated and -cooled pressurized- or boiling-water reactors (PWRs, BWRs); pressurized heavy-water-moderated and -cooled reactors (HWRs); gas-cooled, graphite-moderated reactors (GCRs), in which the gas coolant, either carbon dioxide or helium, flows through a solid graphite moderator; and light-water-cooled, graphite-moderated reactors (LWGRs). These are all thermal reactors, in which the moderator material is used to slow down fast fission neutrons to thermal energies. Fast-breeder reactors (FBRs) at present make only a minor contribution to energy production. Between 1990 and 1994, the number of operating reactors remained relatively stable, increasing slightly from 413 to 432 by the end of the period. A listing of nuclear reactors in operation during the period 1990–1997, the installed capacities and the electrical energy generated is given in annex C of the UNSCEAR 2000 Report [U3], "Exposures to the public from man-made sources of radiation". At the end of 1997, there were 437 nuclear power reactors operating in the world, with a capacity of about 352 GW(e) (net gigawatts of electrical power) [I8]. For the period 1998–2002, the number of nuclear reactors in operation, the installed capacities and the electrical energy generated are given in section II.C.1 of this annex. The average number of power reactors operating in the world over the period 1998–2002 was 444, with an average capacity of about 278 GW(e).

539. In addition to data provided in response to the UNSCEAR Global Survey of Occupational Radiation Exposures, data on exposures of workers at nuclear power reactors are also available from the ISOE database [O14, O19, O20]. The ISOE occupational exposure database includes information on occupational exposure levels and trends for 401 operating reactors in 29 countries, covering about 91% of the world's operating commercial reactors [O22]. The ISOE data on occupational exposures at nuclear power reactors for 1990–2002 [O19, O20] and data from the UNSCEAR Global Survey of Occupational Radiation Exposures combined with information provided in the UNSCEAR 2000 Report [U3] for the various types of reactor are given in table A-21.

540. Occupational exposures can vary significantly from reactor to reactor and are influenced by such factors as reactor size, age and type. Several different broad categories of reactor are currently in operation, including PWRs, BWRs and GCRs (which include older Magnox reactors), as well as a newer generation of reactors, AGRs, HWRs and LWGRs. Within each category, there is much diversity in design and in refuelling schedule, which may contribute to differences in occupational exposure. In addition, changes in operating circumstances can alter the exposure at the same reactor from one year to the next. Some of these variations will be discussed in this section.

541. The type of reactor is only one of the factors influencing the doses received by workers. Other basic features of the reactor play a role, including the piping and shielding configuration, fuel failure history, reactor water chemistry, and the working procedures and conditions. All of these can differ from site to site, even among reactors of the same type, contributing to the differences seen in occupational exposures. At all reactors, external irradiation by gamma rays is the most significant contributor to occupational exposures. The exposures occur mostly during scheduled maintenance and/or refuelling outages. For the most part, such exposures are due to activation products (^{60}Co, ^{58}Co, ^{110m}Ag); however, when fuel failures occur, fission products (^{95}Zr, ^{137}Cs) may also contribute to external exposures. At BWRs, workers in the turbine hall incur some additional external exposure due to ^{16}N, an activation product with an energetic gamma ray that is carried by the primary circulating water through the turbines. In HWRs, heavy water is used as both coolant and moderator. Neutron activation of deuterium produces a significant amount of tritium in these reactors, so in addition to the usual external exposures, workers may also receive internal exposures due to tritium, which is a pure beta emitter.

542. Throughout the world, occupational exposures at commercial nuclear power plants have been steadily decreasing over the past decade, and this trend is reflected in the data for 1995–2002. Regulatory pressure (particularly after the issue of ICRP Publication 60 [I47] in 1991), technological advances, improved plant designs, installation of plant upgrades, improved water chemistry, improved plant operational procedures and training, the involvement of staff in the control of their own doses, and international sharing of ALARA data and experience have all contributed to this decreasing trend. Globally, ISOE includes the world's largest database on occupational exposures at nuclear power plants and provides an international forum for radiation protection experts from both utilities and national regulatory authorities to discuss, promote and coordinate international cooperative undertakings in the area of worker protection at nuclear power plants [O5, O6, O7, O8, O9, O10, O11, O12, O13, O14, O15, O18, O19, O20].

543. Data on occupational exposures for reactors of each type are detailed by country in table A-21, and a worldwide summary by reactor type is given in table 66. Worldwide levels of exposure have been estimated from the data provided; the extrapolations are based on the total energy generated in countries providing data. Very little extrapolation was needed, as the data provided were substantially complete (about 96% for PWRs, 99% for BWRs, 63% for HWRs, 100% for GCRs and 13% for LWGRs). Data provided through ISOE for 1995–2002 are included as provided by ISOE participants. With a few exceptions, the ISO programme includes essentially all reactors worldwide. The annual data reported in response to the UNSCEAR Global Survey of Occupational Radiation Exposures have been averaged over five-year periods, which provide the average effective dose and the number of monitored workers. The ISOE data provided from 1995 to 2002 are given as averages over the periods 1995–1999 (five years) and 2000–2002 (three years), and provide estimates for the collective effective dose. Figures XLII and XLIII illustrate some of the trends. Previous UNSCEAR reports treated FBRs and high-temperature graphite reactors (HTGRs) separately. No data were provided on these in either the ISOE database or the responses to the UNSCEAR Global Survey of Occupational Radiation Exposures, and in the main these types of facility are no longer operational. The UNSCEAR 1993 and 1988 Reports [U6, U7] concluded that they make a negligible contribution to occupational exposure, and therefore they are not considered further.

544. The UNSCEAR 1993 Report [U6] identified the need for more data on measurably exposed workers, as these provide a better basis for the comparison of average doses to individuals than is possible using the monitored worker data. The UNSCEAR Global Survey of Occupational Radiation Exposures now provides good data on measurably exposed workers for PWRs, BWRs and HWRs (see table A-21). The vast majority of the GCRs are in the United Kingdom, and while data matching the definition of "measurably exposed" are not readily available, a good data set showing dose distribution is available from the United Kingdom's Central Index of Dose Information (CIDI) [H8].

545. The procedures for the recording and inclusion of doses incurred by transient or contract workers may differ from utility to utility and country to country, and this may influence the statistics in different ways. In some cases, transient workers may appear in the statistics for a given reactor

several times in one year (whereas they should rather appear only once, with the summed dose being recorded). If appropriate corrections are not made, the statistics so compiled will inevitably overestimate the size of the exposed workforce and will underestimate the average individual dose, as well as the fraction of the workforce receiving doses above the prescribed levels and the fraction of the collective dose arising from these doses. This will only be important where extensive use is made of transient workers and where no centralized reporting database is used.

546. Countries also differ in how they present information on the exposures of workers at nuclear installations. The majority present statistics for the whole workforce, i.e. employees of the utility and contract workers, often with separate data for each category. Other countries provide data for utility employees only, whereas still others present the collective dose for the total workforce but individual doses for the utility employees only. Where necessary and practicable, the data provided have been adjusted to allow them to be fairly compared with other data; these adjustments are indicated in the respective tables.

(i) Light-water reactors

547. PWRs constitute the majority of the installed nuclear generating capacity for the period 1998–2002, followed by BWRs. Averaged over the whole period, about 91% of the total energy was generated in LWRs (of this, about 67% was from PWRs and 24% from BWRs), with contributions of about 4.5% for HWRs, 1% for GCRs and 3.5% for LWGRs. FBRs contribute only about 0.1% of the total energy generated. Experience has shown that there are significant differences between occupational exposures at PWRs and those at BWRs. Each type of reactor is therefore considered separately.

548. *PWRs.* External gamma radiation is the main source of occupational exposure at PWRs. Since in general only a small contribution comes from internal exposure, the latter is only rarely monitored. The contribution of neutrons to the overall level of external exposure is insignificant. Most occupational exposures occur during scheduled plant shutdowns, when planned maintenance and other tasks are undertaken, and during unplanned maintenance and safety modifications. Activation products, and to a lesser extent fission products within the primary circuit and coolant, are the main source of external exposure. The materials used in the primary circuit, the primary coolant chemistry, the design and operational features of the reactor, the extent of unplanned maintenance, etc., all have an important influence on the magnitude of the exposure resulting from this source. The significant changes that have occurred with time in many of these areas have affected the levels of exposure. One of the most important non-standard maintenance operations that is associated with significant dose is the replacement of steam generators. Data on the collective doses associated with maintenance have been collected by the OECD/NEA [O9] and are given in table 67.

549. The average number of PWRs worldwide increased from 78 in 1975–1979 to 266 in 2000–2002. The corresponding increase in average annual energy generated has been somewhat greater, from 27 to 191 GW a. The number of monitored workers at PWRs increased from about 63,000 in 1975–1979 to 283,000 in 2000–2002 (see figure XLII and table 66). Between the first two periods, the average annual collective effective dose increased by a factor of about 2, from 220 to 450 man Sv. A further small increase to 500 man Sv occurred in the third period, followed by a reduction to 415 man Sv in the fourth period. The dose increased again to 506 man Sv and finally decreased to 415 man Sv. Although the number of reactors increased by a factor of around 2 between 1980 and the last period, the collective dose has remained between 400 and 500 man Sv. To see the underlying trend in the efficiency of radiological protection measures in both design and operational procedures, it is more instructive to look at the normalized annual collective dose. Per reactor this increased from 2.8 to 3.3 man Sv over the first two periods but has since dropped to about 2.0 in the last four periods (2.3, 1.7, 2.0 and 1.6 man Sv). The corresponding values for collective effective dose divided by the energy generated are (in chronological order to 2002) 8.1, 8.0, 4.3, and 2.8, 3.0 and 2.2 man Sv/(GW a).

550. The average annual effective dose to monitored workers fell consistently over the first four periods, being 3.5, 3.1, 2.2 and 1.3 mSv, and then increased to 1.9 and 1.7 mSv in the last two periods, an overall reduction of about one half. Overall, the average annual effective dose to measurably exposed workers was about 2.7 mSv for 2000–2002. The dose distribution data also parallel the downward trend in doses, with both NR_{15} and SR_{15} consistently dropping to <0.01 and 0.06, respectively, for the period 2000–2002.

551. There is considerable variation in the worldwide average values with respect to both the trends and the levels of dose in individual countries. In some cases this variation reflects the age distribution of the reactors and the build-up of activity in the cooling circuits. In other cases the reason for it is less obvious. More detailed analysis is contained in the various OECD annual reports [O5, O6, O7, O8, O9, O10, O11, O12, O13, O15, O18, O20].

552. *BWRs.* External radiation is also the main source of occupational exposure in BWRs, with most exposures arising during scheduled shutdowns, when planned maintenance is undertaken, and during unplanned maintenance and safety modifications. By far the largest numbers of BWRs are located in the United States and Japan.

553. Worldwide, the average number of BWRs increased from about 50 in 1975–1979 to about 90 in 2000–2002; the corresponding increase in the average annual energy generated worldwide was somewhat greater, from about 15 to 67 GW a. Overall, 40% of this energy was generated by BWRs in the United States, 25% in Japan, 16% in Germany and Sweden, and the remaining 19% in other countries. On the basis of the UNSCEAR Global Survey of Occupational

Radiation Exposures, the number of monitored workers at BWRs worldwide increased from about 59,000 to about 160,000 at the end of period four, and then decreased to 144,000 and 113,000 in the last two periods (see figure XLII and table 66). The average annual collective effective dose increased from about 280 to about 450 man Sv between the first two five-year periods. It subsequently decreased in the third and fourth periods to about 330 and 240 man Sv, notwithstanding a twofold increase in the energy generated over the same period. For the last two periods the values were 237 and 160 man Sv. The normalized average annual collective effective dose per reactor initially rose from 5.5 to 7.0 man Sv over the first two periods, but dropped to 4.0 and then to 2.7 man Sv in the next two periods, remained constant at about 2.6 man Sv in 1995–1999, then finally decreased to 1.8 man Sv per reactor. The corresponding values normalized to the energy generated were 18, 18, 7.9, 4.8, 3.8 and 2.4 man Sv/(GW a). Both sets of values indicate significant reductions over the six periods.

554. The average annual effective dose to monitored workers over the six periods has consistently fallen: 4.7, 4.5, 2.4, 1.6, 1.7 and 1.4 mSv. There has been a reduction by a factor of about 3 overall. The worldwide average annual effective dose to measurably exposed workers, 2.1 mSv, is about 50% higher than that to monitored workers. The declining trend in doses is also seen in the values of NR_{15} and SR_{15}, with the fraction of the collective dose delivered at individual dose levels of above 15 mSv having been 0.09 in 2000–2002.

555. There is considerable variation in the worldwide average values with respect to both the trends and the levels of dose in individual countries. However, the differences seem to be decreasing over time, and for the vast majority of countries reporting, a downward trend is apparent.

(ii) Heavy-water reactors

556. The worldwide average number of HWRs increased from 12 in 1975–1979 to 39 in 2000–2002. The corresponding increase in the average annual energy generated worldwide was somewhat greater, from about 3 to 13 GW a. The number of monitored workers in HWRs worldwide increased from about 7,000 to about 20,000 over the first four periods, and remained about the same over the last two periods, as shown in figure XLII and table 66. The average annual collective effective dose increased from about 32 man Sv in the first five-year period to about 46 and 60 man Sv in the second and third periods. In the fourth and fifth periods, however, it decreased significantly, to 35 and 29 man Sv, before increasing again to 38 man Sv in the period 2000–2002. The normalized average annual collective effective dose per reactor decreased slightly, from 2.6 to 2.3 man Sv, over the first three periods, and then dropped to 1.1 man Sv and remained constant. The corresponding values normalized by the energy generated fell by a factor of almost 4, from 11 to 2.9 man Sv/(GW a), over the six periods. Both sets of values indicate significant reductions over the six periods.

557. The average annual effective dose to monitored workers fell from 4.8 to 3.2 mSv over the first two periods but remained about the same for the third period. For the fourth period it fell significantly to 1.7 mSv, and became steady again in the last two periods at 1.6 mSv. As before, the reduction overall was by a factor of about 2. The doses due to the intake of tritium (as tritiated water) may have provided an important contribution, around 20%, to the total effective dose [H15].

(iii) Gas-cooled reactors

558. There are two main types of GCR: Magnox reactors, including those with steel pressure vessels and those with prestressed concrete pressure vessels; and AGRs. Another type, HTGRs, reported previously [U7], is no longer in operation. Most of the experience with GCRs has been obtained in the United Kingdom, where they have been installed and operated for many years. Initially the GCRs were of the Magnox type, but throughout the 1980s, the contribution of AGRs, in terms of both installed capacity and energy generated, became more important. The relative importance of AGRs will increase as Magnox reactors are decommissioned.

559. The UNSCEAR 1993 Report [U6] investigated the differences in occupational exposures between Magnox reactors and AGRs. These arise mainly from the use of concrete (as opposed to steel) pressure vessels in the AGRs (and the later generation of Magnox reactors) and from the increased shielding they provide against external irradiation, the dominant source of occupational exposure. The UNSCEAR 1993 Report identified significant differences between the various types, with the average annual effective dose in first-generation Magnox reactors steel pressure vessels remaining uniform at about 8 mSv, whereas the values for Magnox reactors with concrete pressure vessels and for AGRs were less than 0.2 mSv. During the 1990–1994 period, significant dose reductions were made at the Magnox reactors, with further reductions during the last two periods. More detailed information can be found in the reviews of radiation exposures in the United Kingdom [H26, H27]. In this annex no distinction has been made in table 66 between the various types of GCR.

560. The worldwide number of GCRs averaged over five-year periods has decreased significantly from 40 in 1975–1979 to 23 in the last period (2000–2002). Some reactors have been shut down. The number of monitored workers as provided by the UNSCEAR Global Survey of Occupational Radiation Exposures increased overall, from 13,000 in the first period to 30,000 in the fourth, and then decreased to 21,000 and 18,000 in the last two periods, as shown in figure XLII and table 66. The average annual collective effective dose dropped over the six periods, being 36, 34, 24, 16, 7 and 4 man Sv. The normalized collective dose per reactor also decreased over this period, from 0.9 to 0.2 man Sv. The corresponding values for energy generation decreased in the

first five periods from 6.6 to 0.7 man Sv/(GW a) and then increased to 2.6 man Sv/(GW a). The worldwide average annual effective dose to monitored workers, averaged over five-year periods, fell progressively from 2.8 mSv in the first period to 0.2 mSv in 2000–2002. The fraction of the monitored workforce receiving annual doses in excess of 15 mSv has been small, falling from 0.02 by a factor of over 100. Between 1992 and 1994 there was only one instance of a worker at a United Kingdom GCR incurring a dose of over 15 mSv in a year, and only ten workers received doses of over 10 mSv in a year [H27].

(iv) Light-water-cooled, graphite-moderated reactors

561. LWGRs were developed in the former Soviet Union and have only been installed in what are now the Russian Federation, Ukraine and Lithuania. Only data equivalent to 13% of the total energy generated by LWGRs were provided in response to the UNSCEAR Global Survey of Occupational Radiation Exposures, ISOE [O19] and other sources [R22].

562. There is no information available to estimate the worldwide level of exposure. The overall number of LWGRs increased from 12 in the first period to 20 during 1990–1994. The corresponding average annual energy generation increased from 4.4 to 9 GW a. The number of monitored workers increased over the first three periods from about 5,000 to 13,000, but no data are available for the last three periods. The average annual collective effective dose increased significantly, being 36, 62, 173 and 190 man Sv for the four periods from 1978 to 1994. The value for the occupational exposure given here corresponds to the period from 1978 to 1994. There are insufficient data for reliable extrapolation to subsequent periods.

563. It was suggested in the UNSCEAR 1993 Report [U6] that the large increase in collective dose between the second and third periods (62 to 170 man Sv) was artificial in that the data included a significant component from the after-effects of temporary work at Chernobyl. However, the data for 1990–1994 show another increase in exposure. Also, the data from Lithuania tend to support the overall high levels of occupational exposure.

(v) Summary

564. Data on occupational exposure at reactors worldwide are summarized in table 66. The worldwide number of power reactors averaged over the six periods increased from about 190 in the first period to 444 in 2000–2002. The corresponding increase in average annual energy generation was from 55 to 278 GW a. Averaged over the whole period, about 91% of the total energy was generated in LWRs (of this, about 67% was from PWRs and 24% from BWRs), with contributions of about 4.5% for HWRs, 1% for GCRs and 3.5% for LWGRs. The number of monitored workers increased from about 150,000 to 530,000 in the fourth period and decreased to about 440,000 in the last period. The period 1990–1994 is the first for which a reasonably robust estimate of the number of measurably exposed workers, some 290,000, is available; this value dropped to 170,000 for the period 1995–2002.

565. The annual collective effective dose averaged for each of the six periods increased over the first three periods (600, 1,000 and 1,100 man Sv) but fell back to 900, 800 and 600 man Sv in the last three periods. The trends in annual values are shown in table 66 and figure XLIII. About 93% of the collective dose was received by workers at LWRs. Averaged over all the periods, the contribution from workers at HWRs was 6%, at GCRs 1% and at LWGRs about 13%. LWGRs were not considered in this evaluation.

566. The normalized collective effective dose per reactor averaged over all reactors rose over the first two periods, from 3.1 to 3.7 man Sv, but dropped to 2.8, 2.1, 1.5 and 1.1 man Sv over the remaining periods. The corresponding figures per unit energy generated are 10.9, 10.4, 5.7, 3.9, 2.5 and 2.5 man Sv/(GW a) for the six periods. A generally decreasing trend is apparent for both normalized figures for most reactor types. The exception is LWGRs, for which a roughly threefold increase was seen over the first four periods.

567. The annual effective dose to monitored workers averaged over all reactors fell steadily, from 4.1 to 1.0 mSv. This number may be an underestimate, since the data for LWGRs are not included in the dose estimate of the last periods. This downward trend in annual dose to monitored workers is evident for each reactor type except LWGRs, although there are some differences between reactor types in the magnitudes of the doses and in their rates of decline.

568. Data on the distribution ratios NR_{15} and SR_{15} are less complete than data for other quantities, but for 1990–1994 more dose profile information is available for dose bands up to 1, 5 and 10 mSv. Values of NR_{15} and SR_{15} averaged over all reported data are given in table A-21. They show the fraction of monitored workers receiving doses in excess of 15 mSv to be about 0.08 in the first period, decreasing to 0.02 in 2000–2002. The corresponding fraction of the collective dose arising from doses in excess of 15 mSv decreased from 0.60 to 0.13.

569. Information on doses according to job category has been provided through the ISOE programme (table 67). To account for some inhomogeneity in the statistical recording systems, these data have been aggregated into five broad categories: refuelling, maintenance, inspection, servicing and a fifth category covering all other tasks. The data available at the job level in the ISOE database cover European reactors, as well as those in China, South Africa and Brazil.

570. In general, the annual doses associated with most jobs, regardless of reactor type, decreased from the 1995–1999 period (five years) to the 2000–2002 period (three years).

For PWRs, the standardized annual dose due to refuelling showed a 20% decrease. Decreases in doses due to maintenance jobs and servicing jobs of 30% and 10%, respectively, were also observed. A 38% increase in the annual dose due to inspection for all countries over the period 2000–2002 resulted partially from an increase in the number and frequency of controls in France and Germany. For BWRs, doses associated with annual maintenance, inspection and servicing decreased by about 30%, while the annual dose due to refuelling (which is more standardized) remained stable or even showed a small increase.

571. The evolution of doses due to maintenance and servicing for both PWRs and BWRs is the consequence of many factors, including reductions in the duration of refuelling outages and in the number of tasks performed, the implementation of ALARA programmes and better job preparation.

(e) Decommissioning

572. Some nuclear power plants are already in a phase of decommissioning. The workers involved in this process may receive internal and external exposures. When nuclear reactor facilities are dismantled as part of decommissioning a nuclear power station, radioactive dust is generated. This radioactive dust is likely to diffuse in the working environment, resulting in internal exposure. However, most of the dose comes from external exposure. There are few published data available on doses due to decommissioning. Data from 13 nuclear power plants in the United States show that about 2,000 workers were involved in this process in the period 1995–2002. The average annual effective dose for the measurably exposed workers was around 2 mSv and the average annual collective dose was around 4 man Sv. These data are presented in table 68. The available data are not sufficient for evaluating the worldwide level of exposure.

(f) Fuel reprocessing

573. The principal reason for reprocessing has been to recover unused uranium and plutonium in the spent fuel elements. A secondary reason is to reduce the volume of material to be disposed of as high-level waste. In addition, the level of radioactivity in such "light" waste after about 100 years falls much more rapidly than in spent fuel itself. The practice is conducted in only a few countries: France and the United Kingdom have with commercial-scale facilities, Japan and India have experimental facilities, and the Russian Federation has been reprocessing fuel for reactors developed in that country [U3]. In the last decade, interest has grown in separating ("partitioning") individual radionuclides both to reduce long-lived radionuclides in residual waste and to be able to transmute separated long-lived radionuclides into shorter-lived ones. Reprocessing to recover uranium and plutonium avoids wasting a valuable resource, because most of the spent fuel (uranium at less than 1% ^{235}U and a little plutonium) can be recycled as fresh fuel, saving some 30% of the natural uranium that would otherwise be required. It also avoids leaving the plutonium in the spent fuel, where in a century or two the radiological hazard from other components will have diminished significantly, possibly allowing the plutonium to be recovered for use in weapons.

574. Spent fuel assemblies removed from a reactor are highly radioactive and produce heat. They are therefore put into large tanks or "ponds" of water, which cools them and, with three metres of water over the assemblies, shields the radiation they emit. They remain for a number of years either at the reactor site or at the reprocessing plant, and the level of radioactivity decreases considerably with time. For most types of fuel, reprocessing occurs at any time from 5 to 25 years after the fuel is unloaded from the reactor.

575. The exposure data for 1995–1999 and 2000–2002 are given in table A-22. In the earlier period, the contribution of 33.9 man Sv from the Russian Federation accounted for over 50% of the worldwide average annual collective effective dose.

576. The estimate for the worldwide level of exposure was based on the trends in the data from the reporting countries. The number of monitored workers has increased over the six periods, from 8,000 in the first period to 76,000 in the last. The collective effective dose dropped from 53 man Sv in 1975–1979 to 36 man Sv in 1985–1989, increased to 67 man Sv in the following period, and remained steady in the last two periods. The effective dose has decreased progressively, from 7.1 mSv in the first period to 0.9 mSv in the last period. The trends are presented in table 69 and figure XLIV. The increase in collective dose is associated with increased numbers of workers.

(g) Research related to the nuclear fuel cycle

577. It is difficult to estimate the levels of occupational exposure that can unequivocally be attributed to research and development related to the commercial nuclear fuel cycle. Few data are available separately for this category; even when they are, uncertainties remain as to their proper interpretation.

578. Occupational exposures arising in nuclear research are presented in table A-23. There is considerable variation in the levels of collective dose associated with research activities in each country, reflecting, among other things, the relative role of nuclear energy in the national energy supply and the extent to which nuclear technology was developed domestically or imported. The estimate for the worldwide level of exposure was based on the trends in the data from the reporting countries. In the last three periods, the number of monitored workers decreased by about 25%, from 120,000 in 1990–1994 to about 90,000 in 2000–2002. The annual collective effective dose dropped by a factor of 4 over the six periods, from 170 man Sv in 1975–1979 to 36 man Sv in 2000–2002. This fall is a consequence of the reduction in the

effective dose, which fell from 1.4 to 0.4 mSv from the first period to the last. The trends are presented in table 70 and figure XLV.

(h) Waste

579. Radioactive waste arises at all stages of the nuclear fuel cycle in the process of producing electricity from nuclear material. The cycle comprises the mining and milling of the uranium ore, its processing and fabrication into nuclear fuel, its use in the reactor, the treatment of the spent fuel taken from the reactor after use and finally the disposal of the waste. Radioactive waste is classified as low-level, intermediate-level and high-level waste: *(a)* low-level waste is generated by hospitals, laboratories and industry, as well as the nuclear fuel cycle. It comprises paper, rags, tools, clothing, filters, etc., which contain small amounts of mostly short-lived radioactive material. In order to reduce its volume, it is often compacted or incinerated (in a closed container) before disposal. Worldwide it makes up 90% of the volume but only 1% of the radioactivity of all radioactive waste; *(b)* intermediate-level waste contains higher amounts of radioactive material and may require special shielding. It typically includes resins, chemical sludges and reactor components, as well as contaminated materials from reactor decommissioning. Worldwide it makes up 7% of the volume and 4% of the radioactivity of all radioactive waste; *(c)* high-level waste may be the spent fuel itself or the principal waste from its reprocessing. While making up only 3% of the volume of all radioactive waste, it contains 95% of the radioactive material. It includes the highly radioactive fission products and some heavy elements with long-lived radioactivity. It generates a considerable amount of heat and requires cooling, as well as special shielding during handling and transport. If the spent fuel is reprocessed, the separated waste is vitrified by incorporating it into borosilicate (Pyrex) glass which is sealed inside stainless steel canisters for eventual disposal deep underground. On the other hand, if spent reactor fuel is not reprocessed, all the highly radioactive isotopes remain in it, and so the whole fuel assemblies are treated as high-level waste. This spent fuel takes up about nine times the volume of the vitrified high-level waste that would result from reprocessing and encapsulating an equivalent amount of spent fuel, which is then ready for disposal.

580. The doses of the personnel managing radioactive waste depend on the scope of the activities performed. The average annual effective dose for the workers involved in the safe management of spent fuel is in the range 0.2–11 mSv. The level of exposure is lower for the workers involved in waste management (disposal facilities), where the average annual effective dose is in the range 0.2–3 mSv [I38, T4]. Some of these data are presented in table 71.

(i) Summary

581. The trends in worldwide occupational exposures arising from each stage of the commercial nuclear fuel cycle are summarized in table 72 and are illustrated in figures XLVI and XLVII. The data are annual averages over five-year periods, except for the last period, which covers only three years. During the first three periods, the number of monitored workers in the commercial nuclear fuel cycle rose, from about 560,000 to 880,000, but in 1990–1994 it started to fall. The figures for the last three periods are 800,000, 700,000 and 660,000 (figure XLVII). This decrease was largely due to the drastic reduction in the estimated number in the mining sector, from 260,000 to 12,000. For the three last periods, this may be an underestimate, owing to the limitations of the data set, but all other indicators support a significant reduction in this component of exposure of the monitored workforce. In the first five-year period, mining accounted for over 40% of the workforce, but over the subsequent periods, reactor operation became the dominant sector with respect to the number of monitored workers, and at 440,000 it now accounts for about 70% of the total.

582. The average collective effective dose, averaged over five-year periods, initially increased from 2,300 to 3,000 man Sv but in the last four periods decreased to 2,500, 1,400, 1,000 and 800 man Sv (figure XLVII).

583. The average annual effective dose received by monitored workers in the fuel cycle has fallen progressively over the course of the six periods: the values are 4.4, 3.7, 2.6, 1.8, 1.4 and 1.0 mSv. There is considerable variation in these averages for the different stages of the fuel cycle, but overall the downward trend is evident in all nuclear fuel cycle stages. The fraction of monitored workers receiving annual doses in excess of 15 mSv (NR_{15}) averaged over five-year periods has decreased from about 0.20 to about 0.02; the corresponding decrease in the fraction of the collective effective dose (SR_{15}) has been from about 0.63 to about 0.06.

2. Medical uses of radiation

584. Radiation is used in medicine for both diagnostic and therapeutic purposes. Irrespective of the level of health care system, medical uses of radiation increase yearly as the benefits of procedures become more widely disseminated. The medical use of ionizing radiation remains a rapidly changing field, stimulated in part by the high level of innovation by equipment supply companies. The wide range of applications and of procedures and techniques employed in the context of patient exposure are described in annex A, "Medical radiation exposures", which also discusses changes in practice and current trends. Consideration here is limited to the occupational exposures that arise from the application of these medical procedures. The physicians, technicians, nurses and others involved constitute the largest single group of workers occupationally exposed to man-made sources of radiation. Occupational doses received by staff can be differentiated according to the source of exposure, thereby characterizing different occupational groups. There is a need to have an evaluation of these occupational doses according to the main procedures that cause them.

585. There exists a group of individuals who support or comfort patients undergoing radiation treatment or diagnostic procedures. Individuals in this group are generally considered as members of the public, though they can also be workers. The doses for this group of "comforters" are not considered in this annex.

586. The Committee has evaluated occupational exposure for each practice using average values for all workers over five-year periods, without having taken into account the influences of job function and medical procedure on staff exposure. One of the purposes of this annex is to provide significant information on occupational exposure related to the different practices. This will be done by: identifying the job functions and categories of work within each practice that give rise to the more significant exposures; evaluating the contribution of external and internal exposure to the total effective dose; and indicating extremity doses (equivalent doses in hands and lens of the eye).

587. Data from the UNSCEAR Global Survey of Occupational Radiation Exposures for workers involved in all medical uses of radiation are presented in table A-24. The estimation of the worldwide level of occupational exposure was based on the trends from the data reported by countries.

588. The doses used in this annex are those provided by the countries. For this analysis it was assumed that the dose had been estimated taking into account the design of any lead apron used, its thickness and the position of the dosimeter, in particular whether the dosimeter was worn outside the apron or under it, or whether one dosimeter was worn under the apron and a second worn outside it [N11].

(a) Diagnostic radiology

589. Diagnostic examinations with X-rays have been used in medicine for over a century, although with increasing sophistication and new techniques. Medical imaging has experienced a technological revolution resulting in the improved imaging of anatomy, physiology and metabolism [H21]. Steady advances in the quality of X-ray images and in patient protection have ensured a continuing role for diagnostic X-rays in health care, even though alternative modalities for some diagnoses (such as ultrasound and endoscopy) are becoming increasingly available, particularly in developed countries. An increasingly wide range of equipment and techniques are employed to meet a diversity of diagnostic clinical purposes. Variations in occupational doses among six identified subgroups in diagnostic radiology (computed tomography technologists, general radiographers, fluoroscopy technologists, radiologists, nurses and radiologic technology interns) were evaluated. More than 80% of computed tomography (CT) technologists and general radiographers do not have measurable exposure [A8]. On the other hand, the average individual effective dose for interventional procedures is significantly higher than for conventional diagnostic radiology. Medical doctors performing interventional procedures are the most exposed occupational group in diagnostic radiation [K1]. On the basis of such findings, it is no longer appropriate, for example, to treat doses from diagnostic radiology and from interventional procedures together, as the dose average disguises significant differences between them.

(i) Conventional diagnostic radiology

590. Conventional X-ray examinations involve static imaging; the various techniques applied (radiography, CT, mammography and bone mineral densitometry) are described in annex A, "Medical radiation exposures". For radiography, which is the most widely used X-ray application, the average doses depend on the equipment used. For CT, occupational doses are very low and the technique does not represent a significant source of occupational exposure. For mammography, the doses are generally similar to those in CT. In general, the techniques used in conventional radiography do not represent a significant source of occupational exposure.

591. During radiography with fixed installations, the radiographer would normally stand in a control booth that typically is shielded as a secondary barrier against X-ray tube leakage and scattered radiation from the room and the patient. Depending on room size and barrier thickness, the dose to a radiographer in the control booth area is typically less than 1 μSv for a single film taken with a technique of 80 kVp and 40 mA s. Mobile units, however, operate in an unshielded environment and are therefore of greater concern [N10].

592. Occupational exposure arising from the use of CT is usually low, because the primary X-ray beam is highly collimated, and scattered radiation levels are low. In all such CT units, leakage of radiation has been reduced to near zero. For staff in the control room of a properly designed facility, CT does not represent a significant source of exposure.

(ii) Interventional procedures

593. The past four decades have witnessed immense technological advances in radiology. The introduction of image intensification led to the development of interventional radiology. Dotter and Judkins described the first percutaneous treatment of arteriosclerotic vascular obliterations in 1964 [D13], and the range of interventional procedures has dramatically increased since then. This has been accompanied by considerable equipment development. Because of the great advantages of interventional radiology, it is not surprising that both the number and the variety of interventional procedures have grown significantly over the years. Fluoroscopic guidance is frequently utilized in performing many interventional techniques, including precision diagnostic and therapeutic injection procedures. In 29 European countries, the number of coronary angiographies (CA) and PTCA (percutaneous transluminal coronary angioplasty) procedures increased by 264% and 416%, respectively, between

1992 and 2001 [T5, V20]. It is estimated that approximately 1–4 million interventional procedures are performed annually in the United States, with at least 50% performed under fluoroscopy [M5].

594. The development of CT equipment has made possible a variety of clinical applications. One example is CT fluoroscopy, which allows the observation of real-time CT images [K4]. In addition, biopsy examinations performed by CT fluoroscopy offer better accuracy and easier manipulation than conventional examinations. Although the beam for CT is narrow, the tube voltage and current are relatively high. Exposures are unavoidable for medical staff who carry out the examinations. Various surface doses for operating and assisting physicians are shown in table 73. Since examination times differed greatly from case to case, the doses were averaged per minute of fluoroscopy for each set of fluoroscopy conditions [N15].

595. These procedures require the surgeon and assisting personnel to remain close to the patient and thus close to the primary beam of radiation. The advent of complex and prolonged coronary interventional procedures has further increased levels of radiation exposure, although proper procedures and experience can decrease exposures per case. The use of digital imaging, although potentially capable of reducing radiation dose, requires additional constraints on input dosing, fluoroscopy and personnel exposure. Data on the occupational exposure of paediatric cardiologists are sparse, but suggest that technical limitations in working with the smaller patient may adversely affect radiation exposure to physicians and the medical personnel who assist them [K3, L10].

596. Occupational exposures of primary medical doctors involved in interventional procedures vary considerably according to the procedure used. Doses were assessed for different parts of the body according to the type of procedure; results are shown in table 74. The doses resulting from the coronariography procedure are about three times higher than those for angioplasty, arteriography and valvuloplasty. The average time of fluoroscopy can be lower that for the other procedures, but the number of frames is higher [S21].

597. A total of 1,000 consecutive patients with chronic pain undergoing interventional procedures performed by one physician were studied. Two fluoroscopy units were utilized and operated by two certified radiological technologists. The procedures performed included caudal and interlaminar epidural injections, facet joint nerve blocks, percutaneous adhesiolysis, intercostal nerve blocks, sympathetic blocks, transforaminal epidural injections and other procedures. The results showed that these 1,000 patients had undergone 1,729 procedures with an average duration of radiation exposure of 13.2 ± 0.33 seconds per patient and 7.7 ± 0.21 seconds per procedure. Dosimetry measurements indicated an effective dose of 13 mSv (1,345 mrem) outside the lead apron; the measurement inside the apron was below the detection limit. The levels of exposure were significantly below the annual limits recommended [M6].

598. The radiation exposures to three vascular surgeons performing 47 consecutive endovascular aortoiliac aneurysm (EAIA) procedures were determined over a one-year period. The total fluoroscopy time was 30.9 hours (mean of 39.4 minutes per case). The time spent using high-level fluoroscopy varied between 5% and 37%, although in one case it was 60%. The current ranged from 2.1 to 4.7 mA and the tube potential from 65 to 105 kV. Annual effective doses for the primary surgeon, first assistant and second assistant, respectively, were: 1.5, 1.6 and 0.9 mSv under the lead apron, and 13.8, 12.6 and 5.2 mSv outside it. The estimated equivalent doses to the eyes were 7.8, 5.7 and 2.0 mSv for the primary surgeon, first assistant and second assistant, respectively. The estimated equivalent doses to the hands were 18.7, 16.0 and 5.4 mSv for the primary surgeon, first assistant and second assistant, respectively [L16].

599. Occupational doses in interventional cardiology and radiology services at a university hospital are shown in table 75 for the period 1999–2001. According to the data presented in this table, the doses are about the same for all staff if protective measures are undertaken [V9].

600. An evaluation of the occupational exposure to personnel performing cardiac catheterization (dose per procedure) has shown that the range of effective doses for diagnostic catheterizations was 0.02–38 μSv, for percutaneous coronary interventions 0.17–31.2 μSv, for ablations 0.24–9.6 μSv and for pacemaker or intracardic defibrillator implantations 0.29–17.4 μSv. The authors have estimated a reduction in dose of a factor of 4 from 1971 to 2006 for the staff involved in diagnostic catheterizations. For percutaneous coronary interventions, an increasing pattern was observed over time, but this was not statistically significant. The higher radiation exposure for percutaneous coronary interventions was primarily due to the long fluoroscopy times. The contribution of fluoroscopy to the total dose was about 30% for diagnostic catheterizations and 60% for percutaneous coronary interventions [K13].

601. An evaluation of the typical occupational dose levels in interventional radiology and cardiology installations covered a sample of 83 procedures performed by ten specialists in six laboratories [V7]. The monitored staff wore nine thermoluminescent chips sited next to the eyes and on the forehead, neck, hands, left shoulder, left forearm and left arm during each individual procedure. Doses for interventional radiologists and cardiologists are presented in tables 76 and 77, respectively. Radiologists were occasionally out of the room controlling the image acquisition from the system console, and had the lowest dose values. For cardiologists, doses were divided into values measured with and without the use of a protective lead screen. The lowest values correspond to staff who made regular use of the protective screen. The mean dose values for interventional radiologists and interventional cardiologists are presented in figure XLVIII. A more homogeneous distribution was observed for vascular radiologists than for interventional cardiologists. This is because of the variable positions usually adopted by a radiologist with

respect to the patient, while for interventional cardiology procedures, doses are mainly received on the left side, which is closest to the scatter volume throughout the procedure [V7]. The main difference between radiology and cardiology is that, for the former, the X-ray tube is less likely to be rotated and moved during the procedure, and the position of the operator is more variable, depending on the procedure [R5]. There is exposure to scattered radiation not only in the upper part of the operator's body, but to the lower part as well, even though this exposure is at low levels [B33, M5, S21].

602. Different investigators have observed substantial differences in doses received for the same type of procedure. These differences may be as large as an order of magnitude. Many factors influence occupational radiation exposures during fluoroscopy use. No single standardized method has evolved to permit easy comparison of dosimetry results among studies [K13, P1, T11, T12]. The doses vary considerably according to the procedure, operator training and quality assurance. As shown in table 78, occupational doses related to interventional procedures are strongly dependent on several parameters, including: dose rate gradients in the vicinity of the patient; the technique selected (kV, mA or mA s per pulse); the different filtrations available in modern equipment; field size; TV monitor; intensifier size; operational modes (continuous or pulsed fluoroscopy); the number of frames; dose rates; locations inside the room; the typical interventions performed; patient weight and size; design and maintenance of the facility; and the existence and use of protective tools, especially spectacles and ceiling-suspended screens [C1, K3, M10, P12, S37, V8, W15, Z6].

603. National data on occupational exposures arising from X-ray diagnostic radiology over the six periods are presented in the first part of table A-24. Most of the countries have not distinguished between data from conventional and interventional procedures. There is a wide variation in the effective dose and the percentage of measurably exposed workers. This variation may be explained by many factors, including the way data are recorded in the national database, the variety of procedures performed by the medical staff and the protective measures implemented by each country. The worldwide level of occupational exposure is evaluated on the basis of the analysis of trends for the countries. However, the number of workers is derived from the UNSCEAR Global Survey of Medical Radiation Usage and Exposures. The data are presented in table 79 and figure XLIX. They indicate that overall there has been an increase in the number of monitored workers employed in this practice, from 630,000 in 1975–1979 to 6.7 million in 2000–2002, although the number dropped considerably between the third and fourth periods, from 1,350,000 in 1985–1989 to 950,000 in 1990–1994. For the last two periods the estimated value is a factor of 7 higher than for the previous period. The number of workers involved in interventional procedures represents about 0.1% of the total workforce employed in diagnostic radiology. The latest value is more reliable than the previous ones. The collective effective dose increased from 600 to 760 man Sv over the first three periods, dropped by about 40% in the fourth period (1990–1994) and then increased by a factor of 7 to 3,370 man Sv in 2000–2002, following the same pattern as the number of workers. The average effective dose decreased from 0.94 mSv in 1975–1979 to 0.50 mSv in 1990–1994, and has since remained constant.

604. Only a few countries have provided data that distinguish between the workers engaged in conventional techniques and in interventional procedures; the data are presented in table A-25. On the basis of the reported data, about 85% of the monitored workers are involved in conventional radiology techniques. For conventional techniques, the average annual effective dose is about 0.5 mSv (range 0.02–1.24 mSv) for the monitored workers and 1.2 mSv (range 0.33–3.14 mSv) for the measurably exposed workers. For interventional procedures, the average annual effective dose is about 1.6 mSv for the monitored workers and 3.1 mSv for the measurably exposed workers, with a range of 0.4–29.5 mSv. Considerable variation exists in the effective dose and the percentage of measurably exposed workers. This variation may be explained by differences between countries. Greece has provided data for various job categories for interventional radiology: 1) medical doctors—cardiologists; 2) medical doctors—orthopaedists, surgeons, gastroenterologists; auxiliary staff of similar categories; 3) nurses; and 4) others (table A-25 and figure L). It can be seen that cardiologists are the group most exposed. Their average effective dose is 4 mSv, about a factor of 6 higher than the doses for other medical doctor specialists, nurses and other workers. These data are presented separately to indicate that, although these workers are small in number compared with those involved in the conventional diagnostic use of X-rays, their exposure levels are high. As the interventional techniques are being widely applied, the Committee expects that there will be an increasing trend in the number of workers exposed and consequently in the annual collective effective dose.

605. During interventional procedures, the hands of the medical doctors are in the field of radiation, resulting in high exposure to the hands and arms. According to the literature, the equivalent dose to the skin can considerably exceed 500 mSv. During cardiac and abdominal intravascular angiography, a surgeon may receive annual doses to the hands of 440 mSv and 360 mSv, respectively [J1, S35]. There is a large range in the doses reported in the literature. Only a few countries have reported data on extremity doses. The reported values are low, the highest value being around 10 mSv.

(b) Dental practice

606. Diagnostic X-ray machines are widely available and are used frequently in almost every dental office or clinic. The total number of X-ray devices used in dentistry is thus extremely large. Their range of energy is between 20 and 60 keV. Occupational exposure in dentistry is due to scattered radiation from the patient and leakage from the tube head (although the latter should be insignificant with modern

equipment). The general trend over the last 30 or more years has been a dramatic increase in the number of personnel involved in dental radiology coupled with a steady decrease in collective dose. A majority of dental practitioners do not receive measurable doses, and indeed some regulatory authorities do not require routine individual monitoring except where workload is high [U3].

607. National data on occupational exposures arising from dental practice over the period 1995–2002 are given in the second part of table A-24. The worldwide level of occupational exposure is evaluated on the basis of the analysis of trends for the countries. The data are presented in table 80 and figure LI; they indicate a progressive decline in the number of monitored workers involved in this practice. The value first increased from 370,000 to 500,000 in 1980–1984, decreased to 265,000 in 1990–1994 and increased again to 404,000 in 2000–2002. The annual collective effective dose also fell, from 120 man Sv in 1975–1979 to 24 man Sv in 2000–2002. The average annual effective dose decreased from 0.32 mSv in 1975–1979 to 0.06 mSv in 1990–1994, and then remained steady. The percentage of measurably exposed workers has been about the same over the last three periods at around 5%. About 1% of the workforce received doses higher than 1 mSv; there were no recorded doses higher than 5 mSv. Following the trends from the six periods, the predicted number of monitored workers for 2007 would be about 350,000, the collective effective dose would be about 14 man Sv and the average effective dose would be about 0.05 mSv.

(c) Nuclear medicine

608. A broad aim in nuclear medicine is the investigation of physiological processes, with most procedures involving some form of measurement to quantify organ function. The use of radionuclide generators, particularly ^{99m}Tc generators, requires handling tens of gigabecquerels of radioactive material during the elution process. The magnitude of exposures while performing clinical nuclear medicine procedures depends on the precautions taken, including the use of syringe shields when administering injections. Personnel must be close to the patient when giving injections and while positioning the patient and the camera. Usually the imaging process makes the largest contribution to the exposure of staff [B8]. Internal exposures of personnel are usually much lower than external exposures and are controlled by monitoring work surfaces and airborne concentrations, although some medical centres also conduct routine bioassays [N10].

609. Radionuclides used for organ imaging emit penetrating gamma radiation and give rise to exposure of nuclear medicine staff. While some therapeutic procedures are carried out, nuclear medicine departments can generally be characterized by various diagnostic examinations involving intravenous administration of radiopharmaceuticals. Databases on occupational exposure in nuclear medicine rarely distinguish between diagnostic and therapeutic applications. In nuclear medicine, because of the possibility of internal exposure, higher values of annual effective dose are expected for personnel involved in the preparation and assay of radiopharmaceuticals than for medical doctors and nurses.

610. Radionuclides used for organ imaging, for example ^{99m}Tc, emit penetrating gamma radiation and cause exposure of nuclear medicine staff and other persons in the vicinity of patients undergoing diagnosis or treatment. The dose rate at 1 m from a typical diagnostic patient is about 10 μSv/h after the administration of 0.74 GBq of ^{99m}Tc. Therapeutic administrations, for example 3.7 GBq of ^{131}I, give rise to a dose rate of about 200 μSv/h at 1 m from the patient, who therefore will normally be segregated to reduce the exposure of other persons. Work involving the preparation and assay of radiopharmaceuticals is associated with the highest occupational exposures in this field and can give annual doses of up to about 5 mSv. Doses to hands and fingers can range up to the annual limit of 500 mSv. Various shielding devices can be used to reduce extremity doses. However, the majority of workers in nuclear medicine departments who are not directly handling radiopharmaceuticals receive very low exposures, typically less than 1 mSv in a year [N10].

611. An evaluation of effective doses received by the staff involved in tasks with ^{131}I in nuclear medicine has shown that the average annual values range from 0.35 mSv to 3.27 mSv; the maximum dose was around 9 mSv. The evaluation was performed using measurements of ^{131}I in the thyroid [K18].

612. Positron emission tomography (PET) is considered one of the most important diagnostic imaging techniques, having the unique ability to provide functional and quantitative information on the target organ of interest. During recent years, great efforts have been made to improve the diagnostic accuracy of this imaging modality through the development of new acquisition/processing systems and the introduction of new β+-emitting radiopharmaceuticals, all of which has increased the interest of clinicians [Z5].

613. Occupational exposure can be higher by a factor of 2–4 for technologists than for physicians involved in PET procedures. External exposures over a period of one year to four workers (two physicians and two technologists) working full time at a PET centre are presented in table 81. The annual doses ranged from 4.6 to 8 mSv for technologists and were about 2 mSv for physicians. In this centre, an ECAT EXACT HR+ state-of-the-art scanner is used, and ^{18}F-labelled fluorodeoxyglucose (^{18}F FDG) whole-body imaging represents the principal clinical activity (about 96% of the patient workload) [Z5].

614. Table 82 shows the doses for various tasks and patient conditions and for different technologists. Each patient was administered 555 MBq of ^{18}F FDG. The doses varied from below the detection limit for the monitoring technique to 6.8 μSv per procedure. The tasks that result in the largest exposures of the technologist were patient positioning, injection of the dosage and measurement, in that order [M17].

615. Assessments of internal dose for workers from some PET centres in Germany have shown that internal exposure is rather low. Of 79 workers, only 13% received measurable annual doses, which ranged from 0.05 to 1.5 mSv [E7]. Similar values of effective dose were found in an evaluation of occupational exposure at a PET/CT installation in Spain. The doses were 2 mSv for the workers involved in PET/CT; this represents 100 times more than the doses received by workers operating conventional nuclear medicine imaging equipment (0.02 mSv) [C27].

616. The radiation exposure of PET technologists can be quite high and has a large variation. Annual doses have been reported variously as 3, 10 and 12 mSv [B28, R16, Z1]. The annual doses for PET technologists are higher than those for technologists performing general nuclear medicine studies, with values averaging about 3 mSv and 2 mSv, respectively. The estimated average dose per PET procedure was 4.1 μSv (11 nSv/MBq) [R24]. An evaluation of occupational doses received by the technologists in a PET centre has shown that the average daily effective dose was about 14.4 μSv. On average, each technologist administered 831 MBq daily. The mean whole-body dose per MBq injected was 0.02 μSv/MBq. The average daily amount of time at close distances (less than 2 m) from a radioactive source was 32 minutes. The average effective dose per minute of close contact was 0.5 μSv [B20].

617. The assessment of occupational doses to staff working within the imaging section of a PET/cyclotron service in Australia has shown that PET involves higher radiation exposure to staff than do other types of imaging. The average dose per patient for a technologist is calculated at 1.25 μSv. Staff attending sick patients also have increased exposure [C28].

618. Comparison of occupational exposure due to the use of ^{18}F FDG with exposure due to other radiopharmaceuticals used in conventional nuclear medicine procedures (such as gallium scan, bone scan and sestamibi cardiac scans) has shown that PET, high-dose ^{67}Ga and high-dose ^{201}Tl do not represent a significantly greater occupational radiation hazard than conventional nuclear medicine procedures; these data are shown in table 83 [W11, Z5].

619. Within the field of therapeutic applications in nuclear medicine, new agents with beta emitters are being increasingly used. In contrast to most gamma emitters, the energy of beta rays can be totally absorbed in a small delimited tissue volume; thus exposure can be limited to the tissue to be treated. The higher effectiveness of beta radiation is reflected in the higher values of beta ray dose coefficients compared with gamma ray dose coefficients. This leads to dose rates for beta emitters that are two orders of magnitude greater than those of gamma emitters for equal activities and short distances [R14]. The increasing number of medical procedures requires proper attention to extremity doses received by radiopharmacy staff members involved in nuclear medicine. During the preparation of solutions and the handling of waste, local skin doses to the hands of the personnel due to beta emitters can reach very high values. For example, the preparation and application of liquid-filled balloon catheters for vascular brachytherapy resulted in a measured daily equivalent dose at the fingertips of a nuclear medicine specialist that could considerably exceed the recommended annual limit for skin, which is 500 mSv. In other radiosynoviorthesis procedures, it was also estimated that the annual skin dose limit was exceeded owing to direct radiation from beta emitters. In the case of unsealed sources, additional exposures are likely because of possible skin contamination [R14]. These therapeutic applications are in fact a combination of nuclear medicine and radiotherapy.

620. Radiation synovectomy or radiosynoviorthesis (RSO) is a new nuclear medicine procedure in rheumatology and orthopaedics that uses beta emitters. With this treatment it is possible to efficiently treat local chronic inflammatory joint diseases. In radiosynoviorthesis, radioactive colloidal solutions (^{169}Er, ^{186}Re or ^{90}Y) are injected into inflammatory joints. Investigations of exposure to medical staff were performed in ten hospitals and doctors' surgeries. Very high local skin doses were measured both for assistants who prepared the syringes and for physicians who injected the radiopharmaceutical solutions. The local equivalent doses to the skin were up to 100 mSv per working day for assistants and up to 200 mSv per working day for the physicians due to direct radiation [B10]. The very high doses for both assistants and physicians resulted largely from holding the upper end of the cannula between thumb and index finger while connecting or separating the cannula and syringe, or while injecting the radiopharmaceutical solutions into the joint. The highest exposure occurred using ^{90}Y solutions, owing to the high beta energy of ^{90}Y. The use of ^{169}Er causes little direct radiation exposure, but for ^{186}Re, exposure is not negligible. The mean specific dose (local skin dose related to applied activity) was about 60 μSv/MBq (range 13–233 μSv/MBq) for ^{90}Y and about 20 μSv/MBq (4–40 μSv/MBq) when using ^{186}Re. In some cases, considerable skin contamination of personnel occurred. Because of the high specific activities of the solutions (for example about 500 MBq/mL of ^{90}Y), very small, invisible contamination spots may cause high local skin doses [R14].

621. Table 84 shows the maximum daily skin doses for radiosynoviorthesis (RSO) procedures in seven different institutions. Although RSO is a well-established and approved method, it can be carried out differently with respect to details that may considerably influence the radiation exposure of the personnel. In the case of right-handed persons, usually the index finger, thumb and middle finger of the left hand were most exposed, because of the manner of holding the vials or syringes. Doses to the right hand were often lower by an order of magnitude. Lack of knowledge on the part of medical staff of the high exposures from beta radiation can lead to inadequate radiation protection measures being applied in the use of beta-emitting radionuclides during RSO [B9].

622. Radioimmunotherapy following the Zevalin™ procedure (^{90}Y ibritumomab tiuxetan) involves administering the drug for the treatment of patients with relapsed and refractory non-Hodgkin's lymphomas. Zevalin™ consists of an anti-CD20 monoclonal antibody linked to the radioisotope ^{90}Y; the monoclonal antibody component allows radioimmunotherapy to be targeted only towards malignant cells expressing CD20 antigen. The beta radiation of ^{90}Y kills the target cells and other malignant cells in the surrounding area. Immediately before administration, the antibody component must be radiolabelled with ^{90}Y on site; activities of about 2 GBq are handled in this procedure. As a result, medical personnel receive significant partial-body doses if adequate radiation protection measures are not followed. In the Zevalin™ protocol, the preparation of the solution is the critical step before injection. It is essential that a syringe shield and adapted shielding be used, since otherwise the dose to the hands can be extremely high. With radiological protection measures implemented, the maximum local skin dose to the fingertips of the nuclear medicine specialist amounted to 25 mSv per treatment during radiolabelling and administration of the therapeutic dose of Zevalin™ to the patient [A21, R14].

623. At the Academic Hospital of the Free University of Brussels, hand doses have been monitored for several years by means of wrist dosimeters and ring dosimeters (TLDs). Both types are convenient to wear but do not necessarily represent the location on the hand where the highest skin dose is received. The number of manipulations, amounts of activity handled and results from routine monitoring have highlighted the need for more detailed dosimetry for radiopharmacy workers. In this study, two radiopharmacists were monitored during more than 300 manipulations at 18 different locations on each hand. The results expressed in dose per unit activity handled during a specific manipulation showed good reproducibility for individual radiopharmacists. Typical values of $H_p(0.07)$ ranged from 50 to 600 μSv/GBq of handled activity; the fingertips received the highest dose. Particular personal habits in handling radiopharmaceuticals determined the location and the magnitude of skin doses, especially in manipulation of radiopharmaceuticals with high exposure rates such as ^{18}F FDG. The results from this study have shown that annual skin doses would reach about 400 mSv. The principal radiopharmaceuticals that contributed to extremity doses at the hospital were ^{99m}Tc (85%) and ^{18}F (10%), with 5% contributed by other radioisotopes (^{123}I, ^{201}Tl, ^{51}Cr, ^{67}Ga, ^{131}I and others) [B21].

624. National data on occupational exposures arising from nuclear medicine over the six periods are given in the third part of table A-24. The worldwide level of occupational exposure is evaluated on the basis of the analysis of trends for the countries. The data are presented in table 85 and figure LII. They indicate a progressive increase in the number of monitored workers involved in this practice, from 61,000 in 1975–1979 to 120,000 in 2000–2002. The collective effective dose increased from 62 man Sv in 1975–1979 to about 90 man Sv in 1990–1994, and then decreased slightly to 87 man Sv in 2000–2002. The average effective dose decreased from 1.0 mSv in 1975–1979 to 0.7 mSv in 2000–2002. The percentage of measurably exposed workers has been about the same over the three last periods at around 56%. About 30% of the workforce received doses higher than 1 mSv; there were no recorded doses higher than 15 mSv. Following the trends from the six periods, the predicted number of monitored workers for 2007 would be 124,000, the collective effective dose would be 88 man Sv and the average effective dose would be 0.7 mSv. It is important to point out that the recorded doses are related to external exposure. The doses related to nuclear medicine can be underestimated, since there is some contribution from internal exposure, although it is small compared with external exposure.

625. There is a wide variation in the effective dose and the percentage of measurably exposed workers. This variation may be explained by many factors, including the way data are recorded in the national database, the mixing of doses related to exposed workers and non-exposed workers in the database, the mixing of doses from the various procedures performed by the medical staff and the protective measures implemented by each country.

626. In order to obtain improved information about occupational exposures of nuclear medicine workers according to specialty, new questionnaires covering the period 1995–2002 were distributed to Member States requesting information on dose distributions for medical doctors, ward nurses and technicians. Few countries provided information according to worker specialty. A large variation is evident with respect to the estimated average annual effective dose and collective dose; the data are presented in table A-26. The doses for technicians can be substantially higher than the doses for the other staff (medical doctors and nurses). This is to be expected, since the technicians are responsible for the preparation of the injected solutions. However, the doses are dependent on the number of manipulations, the types of radioisotope and the amount of activity handled. Greece has provided data separately for four different job categories: technicians, medical doctors, nurses and others, as illustrated in figure LIII. This shows that the levels of exposure for technicians and medical doctors were higher than for nurses and others. However, the values of average effective doses for the measurably exposed workers were not statistically different.

627. During the preparation of solutions and handling of waste, local skin doses to the hands of the personnel due to beta emitters can reach high values. According to the literature, the equivalent dose at the fingertips of a nuclear medicine specialist can considerably exceed 500 mSv for skin [A21, B9, B10, I59, R14]. There is a large range in the doses reported in the literature. Few countries have reported data on extremity doses, but the values reported are low—around 5 mSv.

(d) Radiotherapy

628. Therapeutic uses of ionizing radiation are quite different in purpose from diagnostic radiology procedures. Radiotherapy

is an important treatment modality for malignant disease (see annex A, "Medical radiation exposures"). In radiotherapy, there are three main treatment categories where occupational exposure may occur: external beam treatment, brachytherapy and therapy simulation. Brachytherapy, where there is manual loading of the radioactive sources, is usually the most significant source of personnel exposure [N10]. Exposures may occur during the receipt and preparation of the sources, during loading and unloading, and during treatment.

629. Personnel are not normally present in the treatment room when external beam therapy is performed, with the possible exception of low-energy (50 kVp and less) X-ray contact therapy units, which are sometimes used for intracavitary treatments. Some exposures can, however, be caused by ^{60}Co teletherapy units as a result of leakage while the source is in the off position and by radiation that penetrates the barrier during use [N10].

(i) Teletherapy

630. The exposures from linear accelerators, betatrons and microtrons depend on the type of beam (photon or electron) and the beam energy. Below 10 MeV, exposure results only from radiation that penetrates the protective barrier. Above 10 MeV, photonuclear reactions can produce neutrons and activation products. The neutrons can penetrate the protective barrier while the unit is operating. Residual activity can expose personnel who enter the treatment room immediately after the treatment has been delivered. The exposures, however, are usually low. Exposures from simulators and other diagnostic imaging equipment used to plan treatments are also usually low [N10].

631. Radiation therapy staff in the treatment rooms of medical accelerators operating with energies of above about 10 MeV are also exposed to radiation due to activated materials. The activation arises primarily from photonuclear reactions and neutron capture. Published estimates of the annual activation dose received by staff during typical operations are in the range 0.7–5 mSv. These numbers demonstrate that the activation dose is not negligible and suggest that, at least in conservatively shielded facilities, the therapist receives a greater occupational dose due to activation than to radiation transmitted through the shielding barriers [A12, R4].

632. Intensity-modulated radiation therapy (IMRT) may play a dominant role in oncology practice in the near future. However, IMRT techniques require a substantial increase in accelerator beam-on time compared with conventional radiation therapy to deliver the same patient dose. This could lead to an increased dose being received by radiation therapists. The increased beam-on time influences radiation exposure in two ways. First, the dose outside the treatment room due to leakage (including neutrons and capture gamma rays) transmitted through secondary barriers will increase, though in principle this can be compensated for by increasing the barrier thickness [M13]. Secondly, in situations where IMRT is delivered using high-energy radiation, the dose inside the treatment room due to induced activation is also expected to increase. The activation dose rates in a treatment room were evaluated for ^{28}Al, ^{56}Mn, ^{24}Na and long-lived isotopes generated at 18 MeV, for different treatment regimes. The largest contribution to doses came from ^{28}Al and ^{56}Mn [R4]. It is worthy of note that the two principal isotopes, ^{28}Al and ^{56}Mn, were also observed to be the dominant isotopes responsible for activation in the treatment room of an accelerator operating at 16 MeV, and interestingly, in the treatment room of a fast neutron facility [Y4]. The isotope ^{24}Na is commonly found in concrete that has been activated by thermal neutrons [N12].

(ii) Brachytherapy

633. Brachytherapy involves the placement of radioactive sources within the body or on its surface so that the radiation source is close to the tissue to be treated. This enables a high dose of radiation to be delivered to malignant tissue and lower doses to normal tissue.

634. Intracavitary brachytherapy is used for the treatment of gynaecological cancers. This involves the placement of radioactive sources into the uterus. Sources can be manually placed into the uterus in a surgical theatre; however, this approach results in the theatre staff, porters and ward nursing staff receiving a high radiation dose. Afterloading was introduced as a means of reducing the radiation dose to staff; in this technique the radioactive sources are remotely placed into position by a treatment machine.

635. A technique of permanent implantation of radioactive seeds into the prostate so that their decay will deliver the prescribed dose to the tumour is in common use. The isotopes used are predominantly ^{125}I and ^{103}Pd. Procedures for seed implantation vary, but there are generally two stages. The first is the manual preloading of needles, which can be performed either by composing loose seeds and spacers or by cutting off strands of seeds and reabsorbable spacers. This process can be done according to a previously approved plan or on the basis of cumulative experience concerning the number of needles and the loading usually needed. The second stage consists of the implantation of these preloaded needles in the operating room. This procedure results in low occupational exposures because of the low activity used per seed and the low energy emitted by ^{125}I. Table 86 shows the mean dose rate levels per implant that best exemplify the dose received by different staff involved during the average 40 min phase of insertion of the seeds into the prostate using the afterloading technique [G4]. The only step in which seeds are not properly shielded is during their movement through the delivery tube, but this process is performed so quickly that it is generally accepted that sufficient protection is provided by stepping back a minimum distance of 50 cm from the tube during the process. Assuming a maximum train of five seeds of maximum activity 40 MBq, the dose rate at 50 cm would be no greater than 0.01 mSv/h [S13].

636. National data on occupational exposures arising from radiotherapy over the six periods are given in the fourth part of table A-24. There is a wide variation in the effective dose and percentage of measurably exposed workers. The worldwide level of occupational exposure is evaluated on the basis of the analysis of trends for the countries. The data are presented in table 87 and figure LIV; they indicate a progressive increase in the number of monitored workers involved in this practice, from 84,000 in 1975–1979 to 127,000 in 2000–2002. The collective effective dose decreased from 190 man Sv in 1975–1979 to 60 man Sv in 2000–2002. The average effective dose decreased from 2.2 mSv in 1975–1979 to 0.5 mSv in 2000–2002. The percentage of measurably exposed workers has been about the same over the last three periods, at around 40%. About 10% of the workforce receives doses higher than 1 mSv; there are no recorded doses higher than 15 mSv. Following the trends from the six periods, the predicted number of monitored workers for 2007 would be about 130,000, the collective effective dose would be about 57 man Sv and the average effective dose would be about 0.5 mSv.

(e) All other medical uses

637. The category "all other medical uses of radiation" was intended to cover new and/or expanding uses of radiation within the medical sector that did not fit into the categories of diagnostic radiology, dental radiology, nuclear medicine or radiotherapy. The principal example has been biomedical research. Educational establishments use radioactive sources, X-ray equipment and unsealed radioactive sources for a wide range of activities. Examples of uses include X-ray crystallography, radioactive labelling (for example using ^{3}H, ^{14}C, ^{32}P, ^{35}S and ^{125}I) and irradiators using ^{60}Co or ^{137}Cs sealed sources [U22]. The UNSCEAR 1993 Report [U6] noted that the lack of consistency in reporting data made it difficult to estimate the level of exposure or to draw useful comparisons for this category of exposure. On the basis of the reported data it is possible to conclude that some countries may not record the data separately according to the techniques used in the medical field. In this case, the doses are reported in "all medical uses".

638. The number of workers potentially exposed in these other uses may substantially exceed those in the few occupations for which data have been separately presented in this section. The average exposure levels of workers involved in other uses of radiation are in general low. However, the way in which the doses are aggregated may disguise somewhat higher average doses in particular occupations. The only way to ascertain the existence of occupations, or subgroups within occupations, that receive doses significantly above the average is for the data to be inspected periodically.

639. National data for the various categories were aggregated by country to give data on exposures to workers arising from all medical uses of radiation; they are presented in table A-27. There is a wide variation in the effective dose and percentage of measurably exposed workers. The analysis of trends for the countries indicates a drastic decrease in the number of monitored workers involved in this practice from 1990–1994 to 1995–1999, and a slight increase of about 20% in the last period. The collective effective dose follows the same pattern as the number of monitored workers. The average effective dose has tended to be the same over the last periods. It is difficult to project with any accuracy the level of exposure for 2007.

(f) Summary

640. National data on occupational exposures arising from all medical uses of radiation averaged over five-year periods are given in table A-27. The Committee has decided to estimate the number of workers on the basis of the UNSCEAR Global Survey of Medical Radiation Usage and Exposures. The average effective dose is estimated on the basis of the data presented in table A-24.

641. The evaluation of trends in occupational exposure for 20 European countries in the medical sector has shown a slight decrease in the average level of exposure. The average collective dose also decreased slightly, from 177 to 171 man Sv, while the average effective dose did not change, having remained at around 1 mSv from 1996 to 2000 [F15].

642. There is a wide variation in the effective dose and percentage of measurably exposed workers. This variation may be explained by many factors, including, the way data are recorded in the national database, the mixing of doses related to exposed workers and non-exposed workers in the database, the mixing of doses from the various procedures performed by the medical staff and the protective measures implemented by each country.

643. For X-ray diagnostics there is a trend of increasing numbers of workers, increasing collective effective doses and relatively constant values for the average effective dose. The estimated number of workers is around 6.74 million, which represents about 90% of the total number of monitored workers involved in the medical uses of radiation. The estimated average collective dose is around 3,370 man Sv, which represents about 95% of the total collective dose for all medical uses. Following the trends from the six periods, the predicted level of occupational exposure for X-ray diagnostic radiology for 2007 would show an increase of 10% in the number of workers and in the average collective dose, and no change in the effective dose. The effective dose has been relatively constant over the last three periods (from 1990–1994 to 2000–2002); this may be due to the influence of the high doses related to interventional procedures. On the basis of the reported data that distinguish between doses from conventional and from interventional procedures, about 0.1% of the monitored workers in diagnostic radiology are involved in interventional procedures. The average annual effective dose due to conventional techniques is about 0.5 mSv (range 0.02–1.24 mSv) for the monitored workers

and 1.2 mSv (range 0.33–3.14 mSv) for the measurably exposed workers. The average annual effective dose for workers involved in interventional procedures is about 1.6 mSv for the monitored workers and 3.1 mSv for the measurably exposed workers, with a range of 0.4 to 29.5 mSv. The doses to the hand can exceed 500 mSv. Although the reported values vary considerably, they are relatively low, and the highest reported value is around 10 mSv.

644. For dental practice there is a trend of decreasing numbers of workers over the six periods (although an increase of about 50% has been observed in the last periods), with decreasing collective effective doses and decreasing average effective doses. The estimated number of workers is about 0.40 million, which represents about 5% of the total number of monitored workers involved in the medical uses of radiation. The estimated average collective dose is 24 man Sv, which represents about 0.7% of the total collective dose for all medical uses. The estimated average effective dose is 0.06 mSv. Following the trends from the six periods, the predicted level of occupational exposure for dental practice for 2007 would show a 10% increase in the number of workers, a decrease of about 5% in the average collective dose and a 3% decrease in the average effective dose.

645. For nuclear medicine there is a trend of increasing numbers of workers, decreasing collective effective doses and decreasing average effective doses. The estimated number of monitored workers is 0.12 million, which represents about 5% of the total number of monitored workers involved in the medical uses of radiation. The estimated average collective dose is 87 man Sv, which represents about 10% of the total collective dose for all medical uses. The estimated average effective dose is 0.7 mSv. Following the trends from the six periods, the predicted level of occupational exposure for nuclear medicine for 2007 would show a 3% increase in the number of workers, a 1% decrease in the average collective dose and a 4% decrease in the average effective dose. These dose projections may be underestimates, since new technologies have been introduced, and the use of new radiopharmaceuticals and ^{18}F FDG has increased considerably. During the preparation of solutions and the handling of waste, local skin doses to the hands of the personnel due to beta emitters can reach very high values, exceeding 500 mSv.

646. On the basis of the data from countries that have reported the doses for the different job categories separately, the Committee concludes that the doses for technicians can be substantially higher than the doses for the other staff (medical doctors and nurses). This is expected, since the technicians are responsible for the preparation of the injected solutions. However, the doses are dependent on the number of manipulations, the types of radioisotope and the amount of activity handled.

647. For radiotherapy there is a trend of increasing numbers of workers, decreasing collective effective doses and decreasing average effective doses. The estimated number of workers is 0.13 million, which represents about 5% of the total number of monitored workers involved in the medical uses of radiation. The estimated average collective dose is 60 man Sv, which represents about 7% of the total collective dose for all medical uses. The estimated average effective dose is 0.5 mSv. Following the trends from the six periods, the predicted level of occupational exposure for radiotherapy for 2007 would show an increase of about 3% in the number of workers, and a decrease of about 5% for both the average collective dose and the average effective dose.

648. For the category "all other medical uses of radiation", which covers new and/or expanding uses of radiation within the medical sector that do not fit into the categories of diagnostic radiology, dental radiology, nuclear medicine or radiotherapy, the analysis is based on data from only one country that has reported the doses for the five practices within the medical uses. The analysis of trends for this country indicates a drastic decrease in the number of monitored workers involved from 1990–1994 to 1995–1999, and an increase of about 20% in the last period. The collective effective dose follows the same pattern as the number of monitored workers. The average effective dose has tended to remain the same over the last several years. It is difficult to project any level of exposure for 2007. These workers represent about 30% of the total number of monitored workers in the practices related to medical uses of radiation. The average collective dose represents about 25% of the total collective dose for all medical uses.

649. The estimated number of workers involved in the medical uses of radiation is 7.40 million, the collective effective dose is 3,540 man Sv and the average effective dose is 0.5 mSv. The evaluation of the trends in occupational exposure for all medical uses together shows an increasing number of monitored workers, and decreasing collective effective dose and average effective dose, as shown in table 88 and figure LV. The largest contribution to the occupational exposure is from diagnostic radiology. The number of monitored workers has increased over the six periods, dominated by those involved in diagnostic radiology.

3. Industrial uses of radiation

650. Radiation sources, including sealed sources, X-ray machines and particle accelerators, are used in a number of industrial applications. Among these are: industrial irradiation; non-destructive testing (particularly industrial radiography); well logging; luminizing; thickness, moisture, density and level gauging; tracer techniques; and fluoroscopic and crystallographic analysis of materials. Because of the many different occupations involved and the ways in which exposures are categorized, it is difficult to obtain comparable statistics in different countries. Most exposures in industrial uses of radiation are low, a fact that contributes to the lack of detail in recorded data. In the UNSCEAR 1993 Report [U6], exposures were considered for those groups of workers that generally experience higher doses:

industrial radiographers, luminizers and well loggers. Workers involved in isotope production and workers employed and monitored at education and research institutes were also assessed. The following categories were introduced in the survey of data for 1995–1999 and 2000–2002: industrial irradiation, industrial radiography, luminizing, radioisotope production, well logging, accelerator operation and all other industrial uses. For the first three periods, the exposure of workers in educational establishments and tertiary education was included within the general category of industrial uses; since the UNSCEAR 2000 Report [U3], these exposures have been included within a "miscellaneous" category in section II.C.4.

651. National data on occupational exposures arising from the industrial use of radiation for the categories mentioned above are given in table A-28. National data for the various categories were aggregated by country to give data on exposures to workers from all industrial uses of radiation; they are presented in table A-29. The Committee has decided not to follow the procedures of the previous UNSCEAR reports to estimate the worldwide level of exposure. The decision was based on the lack of sufficient information to calculate a reliable figure that would reflect the worldwide level of exposure for the last two periods (1995–1999 and 2000–2002). On this basis, it was decided to evaluate the trends for representative countries.

(a) Industrial irradiation

652. The most widespread uses of industrial irradiation are the sterilization of medical and pharmaceutical products, the preservation of foodstuffs, polymer synthesis and modification, and the eradication of insect infestation. The product doses required are extremely high, and the source activities or beam currents are correspondingly high. For gamma facilities the source would typically be ^{60}Co in the petabecquerel range; some ^{137}Cs sources are also used. Dose rates in the irradiation chamber would be of the order of 1 Gy/s, and in some cases there is a need to protect against radiogenic heating that could cause fires. Gamma and electron irradiation facilities must be constructed such that during normal use any radiation exposure of workers will be very low.

653. This category of work was first specified in the previous UNSCEAR Global Survey of Occupational Radiation Exposures [U3]. The available data over the six periods are given in the first part of table A-28; these data are limited and cover only 13 countries. Of crucial importance is the fact that there are very few data from the large industrialized countries, where the greatest number of irradiators are located. It is difficult to evaluate the trend of exposure for lack of information.

654. For this annex, data from China are analysed to show trends over the past periods. Figure LVI indicates an increase in the number of monitored workers, from 100 in 1990–1994 to 1,400 in 2000–2002. The collective effective dose increased from 0.10 man Sv in 1990–1994 to 1.22 man Sv in 1995–1999, and then dropped to 0.88 man Sv in 2000–2002. The average effective dose consistently decreased, from 1.03 mSv in 1990–1994 to 0.63 mSv in 2000–2002. The percentages of measurably exposed workers fell from 90% in 1990–1994 to 63% in 2000–2002 (table A-28). According to the dose distribution data, about 29% of the workers received doses higher than 1 mSv, and 1% of them received doses higher than 15 mSv. As seen in the first part of table A-28, the other countries follow the same pattern of occupational exposure as that described for China, with a decrease in the collective dose and average effective dose. It is difficult to project a level of exposure for 2007 on the basis of the available data.

(b) Industrial radiography

655. Industrial radiography is a non-destructive practice for examining materials for defects. Gamma radiation from ^{137}Cs and ^{60}Co sources as well as X-rays are used to examine welded metal joints. This technique can be applied in three basic formats. The oldest format is direct manual manipulation, either using handling equipment or with the source as an integral part of a shielded "torch". This format, which was prevalent in the 1970s but was already declining in the 1980s, is still used to some extent. Another format has the source in a shielded container; the source can be rotated or moved to produce a collimated beam. This format, too, is being used less frequently. By far the largest amount of gamma radiography is carried out using remote exposure containers. Typically the source is on the end of a drive cable that can be controlled from about ten metres away, so that the source is projected down a flexible tube to the radiography position, where a collimator is normally positioned to reduce the radiation dose to the operators. These devices are portable and are widely used for site radiography. They are also used in fixed-facility radiography, where they can be integrated into the installed safety systems, although this is not always done. The X-ray sets in industrial radiography typically vary in applied voltage from 60 to 300 kV, although there are some 400 kV units. In addition, there are a smaller number of linear accelerators, typically in the range 1–8 MV. These are mostly in fixed facilities with installed safety systems, but there are a few mobile units.

656. Industrial radiography is performed in two quite different situations. In the first, it is carried out at a single location, usually in a permanent facility that has been designed and shielded for the purpose; in this case, items to be radiographed are brought to the facility. In the second situation, the radiography is conducted at multiple locations in the field, in which case the radiographic equipment is brought to the location where the radiograph is required, this procedure often being referred to as "site radiography". There are usually significant differences in the degree of control that can be exercised in the two situations.

657. The available data over the six periods are given in the second part of table A-28. The worldwide estimate of the level of occupational exposure was based on an analysis of the trends in all countries that have provided information; the data are shown in figure LVII. The number of monitored workers increased from 72,000 in 1975–1979 to 116,000 in 1980–1984 and then remained about the same in the last four periods, being 113,500 in 2002. The collective effective dose followed the same pattern as the number of workers, increasing from 190 to 230 man Sv in the first two periods, then dropping to 170 man Sv and remaining constant for the subsequent periods. The average effective dose dropped from 2.6 to 2.0 mSv for the first two periods and remained about the same for the subsequent periods at 1.5 mSv. The percentages of measurably exposed workers dropped from 50% in 1990–1994 to 44% in the last period (2000–2002). According to the dose distribution data, about 30% of the monitored workers received doses higher than 1 mSv, and 1% of them received doses higher than 15 mSv.

658. Following the trends from the six periods, the predicted level of occupational exposure for industrial radiography for 2007 would show an increase of 4% in the number of workers and the average collective dose, and a slight decrease, of 2%, in the effective dose.

659. The different levels of occupational exposure for multiple-location and single-location industrial radiography have been demonstrated by the data from the United States presented in table 89. About 90% of the workforce is engaged in multiple-location industrial radiography. The average collective effective dose for workers involved in single-location work is less than 1% of that for multiple locations. The average effective dose for workers involved in single-location work is about 7% of that for multiple locations [U29, U30, U31, U32, U33, U34, U36, U37, U38].

(c) Luminizing

660. Luminizing is one of the oldest industrial uses of ionizing radiation. In the past, alpha or beta emitters were mixed with a phosphor, such as zinc sulphide, and then painted on dials, such as watch faces or airplane instrumentation. Present-day practice includes using luminizing compounds in gunsights and as low-level light sources for exit signs and map illuminators.

661. The data for the six periods are given in the third part of table A-28. Only three countries have reported data for the periods 1995–1999 and 2000–2002. Switzerland has reported data for most of the periods, allowing the Committee to analyse the trend in occupational exposure over the years. Figure LVIII indicates that the number of monitored workers varied over the six periods, dropping from 210 in 1975–1979 to 130 in the second period, increasing to 350 in 1995–1999 and dropping to 220 in 2000–2002. The collective effective dose consistently decreased, from 2.31 man Sv in 1975–1979 to 0.18 man Sv in 2000–2002. This was due to a decreasing average effective dose, which fell considerably, from 11.2 mSv in 1975–1979 to 0.80 mSv in 2000–2002. The percentages of measurably exposed workers were evaluated for the last two periods, being 98% in 1995–1999 and 93% in 2000–2002. According to the dose distribution data, 22% of the monitored workers received doses higher than 1 mSv, 2% received doses higher than 10 mSv and 1% received doses higher than 15 mSv. Historically the doses to workers involved in luminizing were high, but in recent years there has been a significant reduction. It is difficult to project the level of occupational exposure for 2007 on the basis of only a few countries.

662. On the basis of all the reported data, the average effective doses have decreased over time: 7.44 mSv (1975–1979), 5.01 mSv (1980–1984), 2.71 mSv (1985–1989), 0.38 mSv (1990–1994), increasing to 1.93 mSv in 1995–1999 and dropping to 0.72 mSv in 2000–2002. Except for the period 1995–1999, the trend is a progressive decrease of the effective dose.

(d) Radioisotope production

663. Radioisotopes are produced for a great variety of industrial and medical purposes. The main source of occupational exposure in radioisotope production and distribution is external irradiation; internal exposure may be significant in some cases. In general, however, internal exposures have not been included in reported statistics for occupational exposure except in more recent years, and even then their inclusion is far from universal. Reporting conventions for workers involved in radioisotope production may also vary from country to country (for example with respect to whether the reported doses include only those arising during the initial production and distribution of radioisotopes or whether they also include those arising in the subsequent processing, encapsulation, packaging and distribution of radionuclides that may have been purchased in bulk from elsewhere), and this may affect the validity of comparisons between reported doses.

664. Among the radioisotopes produced, ^{131}I is the one most likely to contribute a significant dose due to internal exposure. However, ^{131}I has gradually been supplanted by other radionuclides with shorter half-lives. In the past, many countries did not record internal exposures. Control of intakes was accomplished mainly through area monitoring, and little emphasis was given to the use of bioassays, mainly because of the cost and the difficulty of interpreting the results. A retrospective study of ^{131}I-contaminated workers in the radiopharmaceutical industry in Brazil has shown that, even with continuously reinforced implementation of safety principles and good practice in handling iodine, committed effective doses can reach values around 4 mSv/a, since the volatility of iodine makes its compounds readily available for intake by inhalation [G1]. The results of internal exposure monitoring on four individuals who worked for seven to ten years in a ^{131}I radiopharmaceutical production laboratory

in the Islamic Republic of Iran showed the maximum and minimum annual intakes to be 536 and 79 kBq, respectively, although one worker (involved in an incident) had an annual intake estimated at 3.8 MBq [A10].

665. The number of cyclotrons dedicated to the production of positron-emitting radionuclides is increasing in medical institutions/hospitals owing to the well-established role of PET imaging in clinical practice. The radiation safety issues in a cyclotron PET facility are much different from those in conventional nuclear medicine facilities because of the presence in a cyclotron PET facility of penetrating gamma photons of 511 keV, higher specific gamma ray constant of positron emitters and the secondary neutrons from the cyclotron during production. Therefore work practices in a cyclotron-PET facility need to be more stringent. The radiation dose to workers in a cyclotron and radiochemistry laboratory measured over 12 months is shown in table 90. The dose received by workers in a cyclotron facility was less than 5% of the annual dose limit (20 mSv) to the whole body and less than 2% of the annual dose limit (500 mSv) to the extremities. Similarly, the doses received by workers in the radiochemistry laboratory were less than 10% of the annual limit to the whole body and less than 1% of the annual limit to the extremities. This was to be expected, as all the operations in this cyclotron and radiochemistry laboratory are completely automated and have adequate shielding [P3]. The evaluation of the occupational exposure in a cyclotron facility in which the total annual activity of ^{18}F and ^{13}N produced was 31 TBq in 2002 (synthesis of ^{18}F FDG represented 90% of the total activity) showed an average annual effective dose of about 7 mSv and an extremity dose of 36 mSv [P8].

666. The occupational doses were found to be 5–10 times less than the regulatory limits in the cyclotron vault, 8–30 times less than the regulatory limits in the radiochemistry laboratory and 10–200 times less than the regulatory limits outside the cyclotron laboratory during beam operation. Internal doses were found to be negligible in the facility [S18].

667. National data on occupational exposures arising from radioisotope production over the period 1995–2002 are given in table A-28. The worldwide level of occupational exposure has been evaluated on the basis of the analysis of individual country trends. The data are presented in figure LIX. They indicate a progressive increase in the number of monitored workers over the first three periods, from 57,000 to 88,000, followed by a drop to 24,000 in 1990–1994, after which the number began to increase by about 4% for each period, resulting in 34,560 in 2000–2002. The collective effective dose fell from 130 man Sv in 1975–1979 to 47 man Sv in 1990–1994, and then increased to 62 man Sv in 2000–2002. The average effective dose decreased from 2.25 mSv in 1975–1979 to 1.12 mSv in 1985–1989, and then increased to about 2 mSv in the last three periods. The percentage of measurably exposed workers has been around 50–70%. About 55% of the workforce received doses higher than 1 mSv, and about 2% received doses higher than 15 mSv. Following the trends from the six periods, the predicted number of monitored workers for 2007 would be 41,472, the collective effective dose would be 75 man Sv and the average effective dose would be 1.8 mSv.

(e) Well logging

668. Well logging is the practice of using radioactive sources or miniature X-ray machines to measure geological characteristics (such as porosity, density and elemental composition) in boreholes drilled for mineral, oil or gas exploration. Well logging has been identified in some countries as an industrial use of radiation that can lead to higher doses to workers than other industrial uses. This is sometimes attributed to the manual manipulation of sources in small spaces, for example on oil rigs. Both gamma and neutron sources are used in well logging, but the contributions from each to the reported doses are generally not indicated.

669. The data on well logging are presented in the fifth part of table A-28. In this practice it is difficult to draw a trend in the level of occupational exposure. Only 12 countries have reported data to UNSCEAR on occupational exposure. Canada is more relevant in terms of the number of monitored workers, representing about 60% of the total reported workforce, and has reported data throughout all the periods. The Canadian data are used to illustrate the trend in occupational exposure for this practice. Figure LX indicates a significant increase in the number of monitored workers in the second period, from 450 in 1975–1979 to 1,010 in 1980–1984. The number was then approximately constant from 1985 to 1999: 1,110 (1985–1989), 950 (1990–1994), 1,060 (1995–1999). It increased in the last period to 1,430. The collective effective dose increased from 0.52 man Sv to 1.37 man Sv in 1985–1989 and dropped to 0.71 man Sv in 2000–2002. The average effective dose was about 1.2 mSv in the first three periods and decreased to 0.50 mSv in 2000–2002. The percentages of measurably exposed workers are between 40% and 70%. It is difficult to project levels of exposure for the year 2007, but they would be expected to reflect increasing numbers of workers and declining average collective dose and average effective dose.

670. On the basis of all the reported data, the average effective doses have decreased over time: 1.32 mSv (1975–1979), 1.17 mSv (1980–1984), 1.07 mSv (1985–1989), 0.36 mSv (1990–1994), increasing to 0.92 mSv in 1995–1999 and to 0.96 mSv in 2000–2002. Except for the period 1990–1994, the trend is a progressive decrease of the effective dose.

(f) Accelerator operation

671. Consideration is limited here to occupational exposures arising from accelerators used for nuclear physics research at universities and at national and international laboratories. Accelerators (generally of somewhat smaller size) are increasingly being used for medical purposes, i.e.

therapy and radiopharmaceutical purposes; however, the exposures arising from those uses are more appropriately associated with exposures arising from the medical uses of radiation. Similarly, accelerators are also found in radiography and commercial radioisotope production, but again these are dealt with under those work categories. Most exposures resulting from accelerators arise from induced radioactivity and occur mainly during the repair, maintenance and modification of equipment. They result mainly from gamma radiation from the activation of solid surrounding materials by penetrating radiation. The potential for internal exposure in the normal operation of accelerators is slight, and doses via this route are negligible in comparison with those due to external irradiation.

672. Early high-energy accelerators used internal targets to produce either radioisotopes or secondary beams of normally unstable particles. Very high levels of activation products were produced in the region of the targets, and before 1960, typical annual collective doses per accelerator were 1–2 man Sv. Such doses still apply for many of the early cyclotrons that remain in operation. Between 1960 and 1980, beam extraction techniques were improved, which led to reduced levels of activation products. However, these reductions were largely offset by the continuing increases in beam power.

673. In the 1980s, two developments had an important influence on occupational exposures at accelerators. The first was the increasing importance of colliding beam techniques for the production of events of interest to the particle physics community. Average beam intensities, as measured by the number of particles accelerated per day, are several orders of magnitude lower than those used in fixed-target physics experiments. Consequently the production of activation products has been greatly reduced, and this is reflected in the exposures of maintenance personnel. The second development was a move towards heavy-ion operation, where again the accelerated beam intensities are several orders of magnitude lower than those with proton acceleration. This has also led to a decrease in activation products and consequently in the exposures during maintenance.

674. The available data are shown in the sixth part of table A-28. In the first three periods, from 1975 to 1989, the reported data were dominated by those of the United States. Since 1990, Canada has contributed the majority of the number of monitored workers. Data from Canada are used to illustrate the trend in occupational exposure for this practice. Figure LXI indicates a significant increase in the number of monitored workers in the first three periods: 580 (1975–1979), 880 (1980–1984) and 1,000 (1985–1989). The number then decreased slightly to 888 in 2000–2002. The collective effective dose increased from 0.17 man Sv in 1975–1979 to 1.06 man Sv in 1985–1989, and then decreased to 0.44 man Sv in 2000–2002. The average effective dose increased from 0.30 mSv in 1975–1979 to 1.1 mSv in 1985–1989, and then decreased to 0.5 mSv in 2000–2002. The percentages of measurably exposed workers are between 26% and 50%, with the highest number in the period 1985–1989. The decrease in the collective dose over the last two periods is influenced by the decrease in average effective dose. According to the dose distribution data, 12% of the monitored workers received doses higher than 1 mSv and 2% of them received doses higher than 5 mSv.

675. On the basis of all the reported data, the average effective doses decreased in the second period and then kept constant over time: 1.62 mSv (1975–1979), 0.76 mSv (1980–1984), 0.62 mSv (1985–1989), 0.75 mSv (1990–1994), 0.62 mSv (1995–1999) and 0.74 mSv (2000–2002).

676. Following the trends from the six periods, the predicted level of occupational exposure for accelerator operation for 2007 would show an increase of about 3% in the number of workers and a decrease of about 10% in the average collective dose and the average effective dose.

(g) All other industrial uses

677. There are many other uses of radiation in industry, for example in soil moisture gauges, thickness gauges and X-ray diffraction, but occupational exposure data for these are in general not separately identified or reported. This category of practice has been incorporated into the UNSCEAR 2000 Report [U3] to accommodate the data from all the other practices not mentioned under the industrial uses of radiation. The number of workers potentially exposed in these other uses may substantially exceed the number in the few occupations for which data have been separately presented in this section. The average exposure levels of workers involved in “other uses of radiation” are in general low. However, the way in which the doses are aggregated may disguise somewhat higher average doses in particular occupations. The only way to ascertain the existence of occupations, or subgroups within occupations, that receive doses significantly above the average is for the data to be inspected periodically.

678. The available data are shown in the last part of table A-28. Japan, Germany and France represent about 87% of the reported monitored workers. It certainly is the case that the national systems for collecting such data do not allow the data to be readily separated into the categories used in this review. Although the Netherlands represents just 2% of the total number of reported monitored workers, it is used to illustrate the trend in occupational exposure for this practice, since it has reported data for most of the practices related to industrial uses of radiation. The number of monitored workers has decreased from 2,880 in 1990–1994 to 2,180 in 2000–2002. The collective effective dose decreased from 0.22 man Sv in 1990–1994 to 0.15 man Sv in 2000–2002. The average effective dose remained steady at 0.08 mSv in 1990–1994 and 0.07 mSv in 2000–2002. The percentages of measurably exposed workers were about 20%. According to the dose distribution data, about 1% of the monitored workers received doses higher than 1 mSv.

679. For the great majority of the reported data, the average effective dose was very low, less than 1 mSv. On the basis of the reported data, the average effective dose was 0.45 mSv in 1990–1994, 0.27 mSv in 1995–1999 and 0.26 mSv in 2000–2002.

680. Following the trends from the six periods, the projected level of occupational exposure for all other industrial uses for 2007 would show an increase of about 2% in the number of workers, and a decrease of about 10% in the average collective dose and the average effective dose.

(h) Summary

681. Table A-29 shows the national data from all industrial uses of radiation grouped together. The data are more complete than for the separate categories of industrial uses of radiation, but as with the data for medical uses they suffer from incomplete data for the United States, which is important in the estimation of worldwide exposure. The Committee has decided not to follow the procedures of the previous UNSCEAR reports to estimate the worldwide level of exposure. The decision was based on the lack of sufficient information to calculate a reliable figure that would reflect the worldwide level of exposure. The estimate of the worldwide level of occupational exposure for all industrial uses was based on the trends for all countries and all practices.

682. The trends in the worldwide level of exposure over the six periods are presented in figure LXII. The total number of monitored workers involved in the practices related to the industrial uses of radiation increased by a factor of 1.6, from 530,000 in 1975–1979 to 870,000 in 2000–2002; it is dominated by industrial radiography. The collective effective dose decreased by a factor of 3, from 870 man Sv in 1975–1979 to 348 man Sv in 2000–2002. The average effective dose decreased by a factor of 4, from 1.6 in 1975–1979 to 0.4 mSv in 2000–2002.

683. The evaluation of the trend of occupational exposure in 21 European countries in general industries has shown an slight decrease in the level of exposure. The average effective dose decreased from 2.0 to 1.8 mSv and the average collective dose decreased from 76 to 69 man Sv in the period 1996–2000 [F15].

684. There is a wide variation in the effective dose and the percentage of measurably exposed workers. This variation may be explained by many factors, including the way data are recorded in the national database, the mixing of doses related to exposed workers and non-exposed workers in the database, and the protective measures implemented by each country.

685. For industrial irradiation there is a trend of increasing numbers of workers and decreasing collective effective dose and average effective dose. Industrial irradiation represents about 3% of the total number of monitored workers in the practices related to industrial uses of radiation. The average collective dose represents about 3% of the total collective dose for all industrial uses. There is not sufficient information to have a statistically significant prediction for 2007.

686. The trend of occupational exposure in industrial radiography is an increase in the number of workers and the average collective effective dose and a decrease in the average effective dose. Industrial radiography represents about 20% of the total number of monitored workers in the practices related to industrial uses of radiation. The average collective dose represents about 55% of the total collective dose for all industrial uses. Following the trends from the six periods, the predicted level of exposure for 2007 would show an increase of about 4% in the number of workers and the average collective dose and a decrease in the effective dose of about 3%.

687. For luminizing there is a trend of an increasing number of workers and a decrease in the collective effective dose and the average effective dose. Luminizing represents about 0.3% of the total number of monitored workers in the practices related to industrial uses of radiation. The average collective dose represents about 1% of the total collective dose for all industrial uses. There is not sufficient information to have a statistically significant prediction for 2007.

688. For radioisotope production there is a trend of an increasing number of workers and a decrease in the average collective effective dose and the average effective dose. Radioisotope production represents about 3% of the total number of monitored workers in the practices related to industrial uses of radiation. The average collective dose represents about 10% of the total collective dose for all industrial uses. Following the trends from the six periods, the predicted level of exposure for the year 2007 would show an increase of about 20% in both the number of workers and the average collective dose, and no change in the average effective dose.

689. For well logging there is a trend of a slightly increasing number of workers, and a decrease in the average collective effective dose and the average effective dose. Well logging represents about 0.4% of the total number of monitored workers in the practices related to industrial uses of radiation. The average collective dose represents about 1% of the total collective dose for all industrial uses. Following the trends from the six periods, the predicted level of exposure for 2007 would show an increase of about 4% in the number of workers, a decrease of about 5% in the average collective dose and a decrease of 10% in the average effective dose.

690. For accelerator operation there is a trend of a slightly increasing number of workers, and a decrease of the average collective effective dose and the average effective dose. Accelerator operation represents about 0.3% of the total number of monitored workers in the practices related to industrial uses of radiation. The average collective dose represents about 1% of the total collective dose for all industrial

uses. Following the trends from the six periods, the predicted level of exposure for 2007 would show an increase of about 3% in the number of workers and a decrease of about 10% in the average collective dose and the average effective dose.

691. For all other industrial uses there is a trend of a slightly increasing number of workers and a decrease in the average collective effective dose and the average effective dose. All other industrial uses represent about 73% of the total number of monitored workers in the practices related to industrial uses of radiation. The average collective dose represents about 29% of the total collective dose for all industrial uses. Following the trends from the six periods, the predicted level of exposure for 2007 would show an increase of about 2% in the number of workers and a decrease of about 10% in the average collective dose and the average effective dose.

692. In summary the number of monitored workers has increased over the six periods. The average annual effective doses to monitored workers involved in industrial uses of radiation have consistently decreased over the six periods. The greatest contribution to the occupational exposure comes from industrial radiography.

4. Miscellaneous uses

693. There remain a number of occupations where radiation exposure may be involved that are not covered by other categories. These include research in educational establishments, radiology in veterinary medicine, the management of spent radioactive sources, transport of radioactive material and others. The data reported by countries are given in table A-30. The Committee has decided not to follow the procedures of the previous UNSCEAR reports to estimate the worldwide level of exposure. The decision was based on the lack of sufficient information for the last two periods (1995–1999 and 2000–2002) to calculate a reliable figure that would reflect the worldwide level of exposure. On this basis, it was decided to evaluate the trend for representative countries.

(a) Educational establishments

694. Research workers in educational establishments use radioactive sources, X-ray equipment and unsealed radioactive sources for a wide range of activities. Examples of uses include X-ray crystallography, radioactive labels (e.g. ^{3}H, ^{14}C, ^{32}P, ^{35}S, and ^{125}I) and irradiators using ^{60}Co or ^{137}Cs sealed sources. In the UNSCEAR 1993 Report [U6], it was noted that the lack of consistency in reporting data made it difficult to estimate the level of exposure and to draw useful comparisons for this category of exposure. Data that should rightfully be attributed to this category are often attributed to other broad practices of radiation, such as research related to the nuclear fuel cycle or industrial uses, and vice versa. The intent here is to include exposures arising in tertiary educational establishments (universities, polytechnics and research institutes with a major educational role). Exposures resulting from research related to the nuclear fuel cycle and from such activities as the use of accelerators should have been included in those more specific occupational categories.

695. The data reported by countries are given in the first part of table A-30. The worldwide level of occupational exposure is evaluated on the basis of the analysis of trends for the countries. The data are presented in figure LXIII; they indicate a progressive increase in the number of monitored workers, from 140,000 in 1975–1979 to 446,000 in 2000–2002. The collective effective dose decreased from 74 man Sv in 1975–1979 to 38 man Sv in 2000–2002. The average effective dose decreased from 0.55 mSv in 1975–1979 to 0.09 mSv in 2000–2002. The percentage of measurably exposed workers has been about 10%. About 2% of the workforce received doses higher than 1 mSv; there are no records of doses higher than 5 mSv. Following the trends from the six periods, the predicted number of monitored workers for 2007 would be 513,360, the collective effective dose would be 42 man Sv and the average effective dose would be 0.08 mSv.

(b) Veterinary medicine

696. Diagnostic radiography is the main source of occupational exposure in veterinary practice. In general, effective doses to individuals should be low, because they arise essentially from scattered radiation. However, poor practice may result in the unnecessary exposure of extremities if, for example, assistants hold animals in position while the radiograph is being taken. The data from the UNSCEAR Global Survey of Occupational Radiation Exposures are given in the second part of table A-30. The main contributions of data for 1995–1999 and 2000–2002 came from Canada, Germany and the United Kingdom, and to a lesser extent from Denmark and the Netherlands. The United States made the largest contribution of data for the first three periods but has not reported since then.

697. National data on occupational exposures arising from veterinary medicine are given in the second part of table A-30. The worldwide level of occupational exposure is evaluated on the basis of the analysis of individual country trends. The data are presented in figure LXIV. They indicate a progressive increase in the number of monitored workers from 48,000 in 1975–1979 to 160,000 in 1985–1989, followed by a drop to 45,000 in 1994–1999 and then an increase to 119,030 in 2000–2002. The collective effective dose increased from 25 man Sv in 1975–1979 to 52 man Sv in 1985–1989, decreased in 1990–1994 to 8 man Sv and increased to 18 man Sv in 2000–2002. The average effective dose decreased consistently, from 0.52 mSv in 1975–1979 to 0.15 mSv in 2000–2002. The percentage of measurably exposed workers has been around 30%. About 3% of the workforce received doses higher than 1 mSv; there are no recorded doses higher than 5 mSv.

698. For the great majority of the reported data, the average effective dose was very low over the six periods, less than 1 mSv. The effective doses decreased from 0.73 mSv in 1975–1979 to 0.10 mSv in 2000–2002. The dose distribution has shown that, for the last period, 12% of the 34,540 workers received doses higher than 1 mSv; there are no recorded doses higher than 5 mSv.

699. Following the trends from the six periods, the predicted level of occupational exposure for veterinary medicine in 2007 would show an increase of about 10% in the number of workers; the average collective effective dose would not change, and the average effective dose would decrease by about 8%.

(c) Spent sources

700. Spent radioactive sources result from industrial applications, research and medicine. A survey was performed in Turkey on the management of such spent sources (^{60}Co, ^{137}Cs) at the Waste Processing and Storage Facility, where 11 ^{137}Cs sources (total activity 851 GBq) and four ^{60}Co sources (total activity 27.75 GBq) that had been used as levels and density gauges were conditioned. Reinforced metal drums (200 L in volume) and cement matrix were used for conditioning of these sources to achieve greater confinement for long-term storage. The maximum dose rates at the surface of the conditioned waste packages were 1.60 mSv/h for ^{137}Cs and 1.63 mSv/h for ^{60}Co. Measurements of the final waste packages were presented to fulfil the requirements (<2 mSv/h) of transport according to the regulations for the safe transport of radioactive material [O23].

(d) Transport

701. Essentially all commercially produced radioisotopes eventually need to be transported by air, land or sea, depending on the source size and the regulatory control provisions. In the course of transport, some radiation exposure of the carriers' staff occurs. According to the IAEA, the annual doses due to transport of radioactive material are in the range 0.2–7 mSv, with an average of about 1 mSv [I42]. The highest doses from transport of radioactive material are to drivers/handlers carrying radiopharmaceuticals. The annual doses to those transporting nuclear fuel is generally low.

702. An evaluation of the occupational doses due to transport was conducted in Canada [E2]. It covered the period 1997–2002 and included 17 companies at 25 sites: a courier company, eight trucking companies, a provincial highway department whose workers transported and used moisture gauges containing radioactive material, a manufacturer, a hospital and a university with shipping/receiving workers, companies involved in internal transport, air cargo terminals, a railway and a port. Overall, nearly 90% of the annual doses in the current study were below 1 mSv. The study participants likely to receive higher doses were the employees of courier companies who physically carried radioactive sources and the drivers/helpers/sorters of radioisotopes for medical use. The histograms in figure LXV show the fractions of annual doses in three dose ranges: <1 mSv, 1–5 mSv and >5 mSv.

703. An important factor in determining worker doses appears to be the size and weight of the package. Small, light packages, such as those handled by couriers, are usually touched, handled and carried close to the body. Intermediate-sized packages, such as those handled by air cargo handlers, are usually moved by handcart, conveyor belt or truck. Large packages, such as those handled in a port or railway yard, or by some truckers, are usually handled only by remote-controlled equipment. Thus doses are inversely related to package size and weight.

704. A survey of the radiological impact of the normal transport of radioactive material by air in the United Kingdom has shown that the highest doses are to handlers carrying radiopharmaceuticals, including ^{131}I and ^{201}Tl, and technetium generators. The average annual effective doses were given as 1–2 mSv and the maximum annual dose was 3.75 mSv. The annual collective dose for the entire handling workforce in the United Kingdom was about 0.1 man Sv. The doses received by the aircrew were very low. The average annual effective doses for aircrew in short- and long-haul passenger flights were 0.003 mSv and 0.064 mSv, respectively (the respective collective doses are 0.13 man Sv and 3.8 man Sv). The average annual effective doses for flight crew of short-haul passenger and cargo flights are 0.0003 mSv and 0.001 mSv, respectively (the respective collective doses are 0.0025 man Sv and 0.024 man Sv). The average annual doses for flight crew in long-haul passenger and cargo flights are 0.007 mSv and 0.036 mSv, respectively (the respective collective doses are 0.13 man Sv and 0.56 man Sv) [W3].

705. A recent survey of occupational exposure related to transport in the United Kingdom of material containing NORM has shown that the maximum annual effective dose to a transport worker would be less than 0.2 mSv [H30].

(e) Other occupational groups

706. The "other occupational groups" category was included in the UNSCEAR Global Survey of Occupational Radiation Exposures to ensure that no sizeable group of exposed persons was overlooked. The data cover disparate groups that often cut across the other categories. This category was incorporated into the UNSCEAR 2000 Report. The data reported by countries are given in the third part of table A-30. As China (Taiwan) has reported data for all three periods recorded and represents about 20% of the reported number of monitored workers, it was selected as an example to evaluate the trend in occupational exposure. There has been a considerable increase in the number of monitored workers, from 1,990 in 1990–1994 to 3,570 in 2000–2002. The collective effective

dose decreased from 1.02 man Sv in 1990–1994 to 0.17 man Sv in 2000–2002. The average effective dose decreased drastically over three of the periods, from 0.51 mSv in 1990–1994 to 0.05 mSv in 2000–2002. The percentages of measurably monitored workers decreased from 34% in 1990–1994 to 6% in 2000–2002. The decreasing collective dose is correlated with the decreasing effective dose.

707. The use of X-rays for security purposes has been reported by two countries in the UNSCEAR survey. Detailed data of occupational exposure for border policeman and customs personnel have shown that the effective doses range from 0.3 mSv to 2 mSv.

708. For the great majority of the reported data, the average effective dose is low over the periods: it decreased from 1.03 mSv in 1990–1994 to 0.17 mSv in 2000–2002. The dose distribution has shown that, for the last period, 4% of the 21,580 workers received doses higher than 1 mSv; there are no recorded doses higher than 5 mSv.

709. Following the trends from the six periods, the predicted level of occupational exposure for other occupational groups for 2007 would show an increase of about 10% in the number of workers, a decrease of about 20% in the average collective effective dose and a decrease of 30% in the average effective dose.

(f) Summary

710. Table A-30 shows the national data from all other categories of workers not included in the categories of natural radiation exposures, nuclear fuel cycle, and medical and industrial uses of radiation. Data that should rightfully be attributed to the miscellaneous uses of radiation include exposures arising in tertiary educational establishments (universities, polytechnics and research institutes with an important educational role), veterinary medicine and all other uses of radiation involving occupational exposures. Exposures resulting from research related to the nuclear fuel cycle and from such activities as the use of accelerators should have been included in those more specific occupational categories.

711. There is a wide variation in the effective dose and percentage of measurably exposed workers. This variation may be explained by many factors, including the way data are recorded in the national database, the mixing of doses related to exposed workers and non-exposed workers in the database, and the protective measures implemented by each country.

712. For educational establishments there is a trend of increasing numbers of workers, increasing collective effective dose and decreasing average effective dose. Educational establishments represent about 61% of the total number of monitored workers in the "miscellaneous" class. The average collective dose represents about 45% of the total collective dose for all categories classified as miscellaneous. Following the trends from the six periods, the predicted level of occupational exposure for educational establishments for 2007 would show an increase of about 15% and 10% in the number of workers and the average collective effective dose, respectively, but a decrease of about 15% in the average effective dose.

713. For veterinary medicine there is a trend of increasing numbers of workers, no change in the collective effective dose and a decreasing average effective dose. Veterinary medicine represents about 17% of the total number of monitored workers in the "miscellaneous" class. The average collective dose represents about 21% of the total collective dose for all categories classified as miscellaneous. Following the trends from the six periods, the predicted level of occupational exposure for veterinary medicine for 2007 would show an increase of about 10% in the number of workers and in the average collective effective dose, but no change in the average effective dose.

714. For all other categories of workers there is a trend of increasing numbers of workers and decreasing collective effective dose and average effective dose. These other categories represent about 22% of the total number of monitored workers in the "miscellaneous" class. The average collective dose represents about 34% of the total collective dose for all categories classified as miscellaneous. Following the trends from the six periods, the predicted level of occupational exposure for "other occupational groups" for 2007 would show an increase of about 10% in the number of workers and a decrease of about 20% and 30% in the average collective effective and the average effective dose, respectively.

D. Man-made sources for military purposes

715. Radiation exposures of workers in military activities can be grouped into three broad categories: those arising from the production and testing of nuclear weapons and associated activities; those arising from the use of nuclear energy as a source of propulsion for naval vessels; and those arising from the use of ionizing radiation for the same wide range of purposes for which it is used in civilian spheres (e.g. research, transport and non-destructive testing). Previous UNSCEAR reports reviewed the first two of these activities separately. This approach is no longer continued here, since the countries have not reported the data separately. It is recognized that there may be a degree of overlap between the categories of nuclear facilities and also that the limited number of countries responding to the UNSCEAR Global Survey of Occupational Radiation Exposures constrains the conclusions that can be drawn. National data on occupational exposure resulting from all military activities are presented in table A-31. Data from the United States and the United Kingdom dominate the reported data on occupational exposure for this practice.

716. In the United States, the USDOE is responsible for stewardship of the nuclear weapons stockpile and the associated facilities, for restoring the environment at related sites

and for energy research [U23]. The facilities covered included accelerators, fuel/uranium enrichment, fuel fabrication, fuel processing, maintenance and support, reactor operation, research, waste management, weapons fabrication and testing. Exposures may arise via two main routes: *(a)* the intake of these materials into the body by inhalation or ingestion (or absorption through the skin in the case of tritium); and *(b)* external irradiation by gamma rays and, to a lesser extent, neutrons. External irradiation tends to be the dominant source of exposure for those involved in the production, testing and subsequent handling of nuclear weapons.

717. The USDOE notes [U23] that the number of monitored workers may not be indicative of the size of the exposed workforce, because some establishments provide dosimetry to individuals for reasons other than radiation protection, e.g. security, administrative convenience and legal liability. As a result, it may not be valid to compare the size of the monitored workforce over time. Similarly, such a large monitored population can confound comparisons of dose. The average effective dose decreased from 1.1 mSv in the first period to 0.1 mSv in the last two periods. It appears to have decreased by a factor of 3 between the periods 1985–1989 and 1990–1994 and by a factor of 1.5 between the periods 1990–1994 and 1995–1999. The annual collective dose at USDOE facilities has experienced a dramatic fall since the first period (1975–1979), from 101 to 13 man Sv. The change in operational status of USDOE facilities has had the largest impact on radiation exposure over the years owing to the shift in mission from weapons production to clean-up activities and the shut down of certain facilities. The USDOE weapons production sites have continued to contribute the majority of the collective dose over these periods.

718. In the United Kingdom, the Atomic Weapons Establishment is the organization whose stewardship is comparable to that of the USDOE. The number of monitored workers in the United Kingdom has stayed roughly constant, at around 12,000. The average annual collective effective dose decreased by a factor of 10 over the first five periods (1975–1979 to 1995–1999), from 36 to 3.6 man Sv, and remained constant between the last two periods. A similar pattern is seen with the average annual effective dose incurred by monitored workers, which over the six periods fell from 3.0 to 0.24 mSv.

719. The UNSCEAR 1993 Report [U6] reviewed the potential for extrapolation on the basis of normalized collective dose, with the normalization performed in terms of unit explosive yield for weapons, and per ship or installed nuclear capacity for the naval propulsion programme. It concluded that such extrapolation was not viable. Pending the acquisition of further data, the UNSCEAR 1993 Report [U6] proposed adopting a very simple approach for estimating worldwide exposures from this source, namely that the worldwide collective dose from military activities is greater by a factor of 3 than the sum of the collective dose in the United Kingdom and the United States. Four assumptions underlay the choice of this factor. First, the levels of military activities in the former Soviet Union and the United States were broadly comparable. Secondly, the levels of exposure in the former Soviet Union were greater than in the United States by an indeterminate amount that did not exceed a factor of 2 in 1975–1989. Thirdly, the levels of exposure in France have been comparable to those in the United Kingdom. Fourthly, the exposures in China were not as large as those in the former Soviet Union or in the United States. The addition in the most recent five-year period of the French data does not significantly change matters, and it is concluded that the above simple approach is still the best available in the circumstances. On the basis of these assumptions, the estimated worldwide number of monitored workers has been roughly constant, at between 300,000 and 400,000 workers. The collective effective dose from military activities would have been about 400 man Sv in 1975–1979, falling to about 250 man Sv in 1985–1989, 100 man Sv in 1990–1994, 58 man Sv in 1995–1999 and 52 man Sv in 2000–2002 (figure LXVI). Given the coarseness of the underlying assumptions, it is not possible to give a precise estimate of the collective dose; perhaps all that can be concluded is that the worldwide average annual collective dose during the period analysed was about 50–150 man Sv. The average effective dose decreased by a factor of 10, from 1.3 mSv in 1975–1979 to 0.14 mSv in 2000–2002. This estimate is inevitably associated with much uncertainty, which can only be reduced by relevant data from other countries involved in weapons production.

720. The above data need to be qualified with regard to their completeness, in particular concerning whether they include all significant occupational exposures associated with military activities. For example, they do not include occupational exposures incurred in the mining of uranium used in either the nuclear weapons or the nuclear naval programmes, nor is it clear to what extent the reported data include exposures arising during the enrichment of uranium for the weapons and naval programmes or exposures arising in the chemical separation and subsequent treatment of plutonium. Such omissions, should they exist, are significant only with respect to the correct assignment of exposures to different practices. Any omission here is likely to be compensated for by an overestimate of exposures in other practices (e.g. exposures in the commercial nuclear fuel cycle).

721. The data presented above for all military activities include occupational exposures for three countries that have developed and deployed nuclear weapons or that have operated nuclear ships, namely France, the United Kingdom and the United States. Any estimate of worldwide occupational exposures from military activities can therefore be made only by extrapolating from the available data. The result will inevitably be only very approximate.

722. The contributions of each category to overall levels of exposure and trends with time are shown in figure LXVII. The worldwide average annual collective effective doses to workers resulting from nuclear fuel cycle operations in the periods 1995–1999 and 2000–2002 are estimated to be about

1,000 and 800 man Sv, respectively. The contribution of practices involving medical uses is estimated to be about 3,540 man Sv for the two periods, which corresponds to about 75% of the total collective dose resulting from all the practices involving the use of man-made sources of radiation (4,960 and 4,730 man Sv for the last two periods). The collective effective dose resulting from occupational exposures to natural sources (at levels in excess of the average levels of natural background radiation) is estimated to be about 37,260 man Sv. The largest component of this, 30,360 man Sv, is associated with mining: 16,560 man Sv due to coal mining and 13,800 man Sv due to other mining operations (excluding uranium mining, which is accounted for in the nuclear fuel cycle). The mineral processing industries were not distinguished from mining operations, since the available data in the literature rarely distinguish the exposure due to mining operations from that due to mineral processing. The new category called "workplaces other than mines" contributes 6,000 man Sv, and the cosmic ray exposure of aircrew contributes 900 man Sv. However, the estimated collective dose due to natural sources of radiation is associated with much greater uncertainty than is the estimated dose due to man-made sources of radiation. The trends are illustrated in figure LXVIII. Trends in exposure due to man-made sources are illustrated in figure LXIX for each of the main occupational categories considered in this annex. For exposure to natural sources of radiation, the evaluation of the level of occupational exposure was first introduced in the period 1990–1994. With respect to earlier periods, the few data that do exist suggest that exposures during mining operations and mineral processing were greater than those estimated here, and possibly much greater, owing to the fact that somewhat less attention was given in the past to the control and reduction of exposures during underground mining.

1. Other exposed workers

723. There is one other group of exposed workers not considered elsewhere, namely those working in diamond mines, where X-ray screening for diamond theft is conducted under certain conditions in some countries. The security measures are implemented to reduce diamond theft and are explicitly authorized through national regulations and cover a large spectrum from access control to the use of special equipment to prevent the employees having direct contact with the diamonds. The radiation dose is due to X-ray screening of workers to detect if they have swallowed or hidden diamonds in their bodies [I6]. There is no reliable estimate of the total number of workers involved in these diamond mines, of how often they are exposed and of the received dose.

E. Summary on occupational exposure

724. Occupational radiation exposures have been evaluated for six broad categories of work: natural sources of radiation, the nuclear fuel cycle, medical uses of radiation, industrial uses of radiation, military activities and miscellaneous uses (which comprise education, veterinary medicine and all other uses involving occupational exposure). In the previous UNSCEAR reports, the worldwide level of exposure was extrapolated on the basis of the reported data applying a different methodology for the practices in the nuclear fuel cycle and for the other practices, such as those in medical, industrial and miscellaneous uses. Inevitably, the data provided in response to the UNSCEAR Global Survey of Occupational Radiation Exposures were insufficient for estimating worldwide levels of dose. Procedures were therefore developed by the Committee to derive estimates of worldwide doses from the data available for particular occupational categories. Two procedures were developed, one for application to occupational exposures arising at most stages in the commercial nuclear fuel cycle and the other for general application to other occupational categories. For the occupational groups involved in practices other than those in the nuclear fuel cycle, the approach used in the UNSCEAR 2000 Report to derive estimates of worldwide doses is no longer used here. For the last two periods, 1995–1999 and 2000–2002, the worldwide level of exposure was derived on the basis of the trends for the countries that provided data. The number of workers exposed to radiation in the medical field is estimated on the basis of the UNSCEAR Global Survey of Medical Radiation Usage and Exposures. In general, the reporting of exposures arising in the commercial nuclear fuel cycle is more complete than that of exposures arising from other uses of radiation. Hence the degree of extrapolation from reported to worldwide doses is less, and this extrapolation can be carried out more reliably than for other occupational categories. Moreover, worldwide statistics are generally available on the capacity and production in various stages of the commercial nuclear fuel cycle. Such data provide a convenient and reliable basis for extrapolating to worldwide levels of exposure.

725. It is difficult to compare the doses among the countries, since there are discrepancies in doses related to the same practice. These can be due to differences in the type of dose that is recorded in the databases, for instance in how the doses below the recording level are recorded, and differences in the criteria for including workers in the individual monitoring programme. Some countries include in their individual monitoring programme workers not who do not work in restricted areas, resulting in an increase in the workforce and a decrease in the average effective dose. Also, some countries record only doses from external exposure, while others record doses from both internal and external exposure. The application of different ICRP methodologies for intake and dose calculations leads to different dose results. This can be an important source of variation in the doses reported by the countries for the period analysed, when most of the countries changed from ICRP Publication 26 [I43] to ICRP Publication 60 [I47] recommendations.

726. Results for the periods 1995–1999 and 2000–2002 are summarized in table 91 and, in abbreviated form, for the whole period of interest (1975–2002) in table 92. The contribution of each category to overall levels of exposure and the trends with time are illustrated in figure XLVII.

727. The total number of workers exposed to ionizing radiation is estimated as approximately 23 million. About 57% are employed in practices that include exposure to natural sources of radiation (13 million workers) and about 43% in practices that include exposure to man-made sources of radiation (10 million workers). For exposure to natural sources of radiation, the greatest number of workers, about 11.50 million, are in mining operations (60% in coal mining and 40% in other mining operations, excluding uranium mining). The estimated number of workers exposed to radon in workplaces other than mines is about 1.25 million, and the number of aircrew exposed to cosmic radiation is 0.30 million. For exposure to man-made sources of radiation, the greatest contribution comes from medical uses of radiation (75% of the number of workers). About 7.40 million workers are involved in medical uses of radiation, 0.66 million in practices related to the nuclear fuel cycle, 0.87 million in practices related to industrial uses of radiation and 0.57 million in other occupational groups, while 0.33 million are involved in military activities.

728. The worldwide average annual collective effective dose to workers exposed to radiation is estimated to be around 42,000 man Sv The worldwide average annual collective effective dose to workers exposed to natural sources of radiation (in excess of the average levels of natural background radiation) is estimated to be around 37,260 man Sv, which represents about 93% of the total collective effective dose. The largest component of this, 30,360 man Sv, comes from mining: 16,560 man Sv due to coal mining and 13,800 man Sv to other mining operations (excluding uranium mining, which is dealt with as part of the nuclear fuel cycle). The mineral processing industries were not distinguished from mining operations, since the available data in the literature rarely distinguish the exposure due to mining operations from that due to mineral processing. The new category called "workplaces other than mines", which includes industries (food industries, breweries, laundries, etc.), waterworks, shops, public buildings and offices, schools, subways, spas, caves and closed mines open to visitors, underground restaurants and shopping centres, tunnels (construction and maintenance) and sewerage facilities, contributes 6,000 man Sv. The contribution of aircrew exposed to cosmic radiation is 900 man Sv. However, the estimated collective dose due to natural sources of radiation is associated with much greater uncertainty than that due to man-made sources of radiation. The trends are illustrated in figure LXVIII. The worldwide average annual collective effective dose to workers exposed to man-made sources of radiation is 4,730 man Sv. The average annual collective effective dose to workers in the nuclear fuel cycle for the period 2000–2002 is estimated to be about 800 man Sv. The contribution of the practices related to medical uses is estimated to be 3,540 man Sv, and of practices related to industrial uses and miscellaneous uses about 400 man Sv. Medical uses of radiation contribute about 75% of the collective effective dose due to exposure to man-made sources of radiation.

729. The average annual effective dose to monitored workers varies widely from occupation to occupation and also from country to country for the same occupation. On the basis of the reported data, the average annual effective dose to monitored workers in industry is less than 1 mSv. In particular countries, however, the average annual dose for some of these occupations is several millisieverts or even, exceptionally, in excess of 10 mSv. The average annual effective doses to workers in the nuclear fuel cycle are in most cases higher than the doses to those in other occupations. For the fuel cycle overall, the average annual effective dose is about 1.4 and 1.0 mSv for the last two periods (tables 72 and 92). For the mining of uranium, the average annual effective dose to monitored workers in countries reporting data fell from 3.9 mSv in 1995–1999 to about 1.9 mSv in 2000–2002. For uranium milling operations, the average annual effective dose fell from 1.6 mSv in 1995–1999 to about 1.1 mSv in 2000–2002. For fuel fabrication, the average annual effective dose is about 1.6 mSv. For reactor operation, the average annual effective dose is 1.5 mSv and 1.0 mSv for the last two periods. However, there are very wide variations around these average values. The doses for decommissioning are around 2 mSv. The individual doses for fuel reprocessing are about 0.9 mSv, whereas those for fuel enrichment are much lower, less than 0.1 mSv.

730. *Trends in exposure over the period 1975–2002*. Trends in exposure resulting from man-made sources are illustrated in figure LXIX for each of the main occupational categories considered in this annex. For exposure to natural sources of radiation, the evaluation of the level of exposure was first introduced in the period 1990–1994. With respect to earlier periods, the few data that do exist suggest that exposures during mining operations and mineral processing were greater than those estimated here, and possibly much greater, owing to the fact that somewhat less attention was given in the past to the control and reduction of exposures during underground mining.

731. The worldwide average annual number of workers involved with man-made uses of radiation is estimated to have increased from about 2.8 million to about 10 million between the first and sixth periods (table 92). The greatest increase (from about 1.3 million to about 7.4 million) was in the number of monitored workers in medicine, which represents about 75% of the workforce. The number of monitored workers for the nuclear fuel cycle also increased significantly in the first three periods, from about 0.6 million in the first period to about 0.9 million in the third period, but it dropped to 0.8 million for 1990–1994 and to about 0.7 million for 1995–2002. The main reason for this significant decrease is the decline in the number of workers in mining operations.

732. The annual collective effective dose averaged over the five years for each of the first three periods (1975–1989) for all operations in the nuclear fuel cycle varied little around the average value of 2,500 man Sv, despite a factor of 3–4 increase in electrical energy generated by nuclear means. The electrical energy generated has continued to

increase, but the average annual collective effective dose fell by a factor of about 2, to 1,400 man Sv, in 1990–1994, and dropped to 1,000 man Sv and 800 man Sv in the last two periods. A significant part of this decrease came from the dramatic reduction in the uranium mining component, from 1,100 man Sv in 1985–1989 to 310 man Sv in 1990–1994, 85 man Sv in 1995–1999 and 22 man Sv in 2000–2002. These last figures may be underestimated owing to limited data, besides which some reported data are related to the decommissioning phase, so they must be viewed with some caution. However, other indicators, such as the reduction in the amount of uranium mined, the closing of many underground mines, a more general move to open-pit mining and the introduction of modern techniques, support the view that a substantial reduction has taken place. In other parts of the nuclear fuel cycle the situation is more varied. In reprocessing, for example, the downward trend in earlier periods—53, 46 and 36 man Sv—has been reversed, with an increase to about 68 man Sv for 2000–2002, associated with an increase in the number of workers. However, apart from mining, the other important element within the nuclear fuel cycle is reactor operation, in which the average annual collective effective dose, after increasing from 600 to 1,100 man Sv over the first three periods, dropped to 900 man Sv for 1990–1994, to 800 man Sv for 1995–1999 and to 620 man Sv for 2000–2002.

733. The average annual effective dose to monitored workers in the nuclear fuel cycle has been consistently reduced over the whole period, from 4.1 mSv to 1.0 mSv. There are some variations between parts of the nuclear fuel cycle and between countries. Of particular note is the fact that, in the first three periods, the dose to monitored workers at LWGRs increased from 6.6 mSv to 13 mSv, and while no specific values for the three latest periods were reported, other indicators at least suggest that the high level of exposure was maintained.

734. The number of monitored workers increased by a factor of 6 over the six periods, from 1.3 million to 7.4 million. The largest increase, from 2.3 million to 7.4 million, was observed in the last two periods (1995–2002), because in this case the estimate was based on more complete information from the UNSCEAR Global Survey of Medical Radiation Usage and Exposures. The worldwide average annual collective effective dose due to all medical uses of radiation, about 1,000 man Sv, changed little over the first three five-year periods. It then dropped significantly, to 760 man Sv, in 1990–1994, but increased to 3,540 man Sv over the last two periods. A clear downward trend is evident in the worldwide average effective dose to monitored workers, which decreased from about 0.8 mSv in the first five-year period to about 0.3 mSv in 1990–1994, then increased in the last two periods, reaching 0.5 mSv in 1990–2002. However, there was considerable variation between countries. For diagnostic radiology, the average effective dose remained constant over the last two periods. This may reflect the influence of the higher doses due to interventional procedures. However, the number of workers increased by a factor of 7, from about 1 million to 6.7 million, between 1990–1994 and 1995–2002. Consequently the collective effective dose has increased in the same proportion as the number of workers.

735. The worldwide average annual collective effective dose due to all industrial uses of radiation was fairly uniform over the period 1975–1984 at about 900 man Sv. It decreased, however, by a factor of almost 2 in the second half of the 1980s (to 510 man Sv) and then fell further, to about 360 man Sv in 1990–1994, and to about 300 man Sv in the last two periods. In general, there was a declining trend in collective dose for the last two periods. However, there was a trend of increasing collective dose for industrial radiography. The same trend is reflected in estimates of individual dose: the average annual effective dose to monitored workers decreased from about 1.6 mSv in 1975–1979 to 1.4 mSv in 1980–1984, 0.9 mSv in 1985–1989, 0.5 mSv in 1990–1994 and 0.3 mSv in 2000–2002.

736. It should be noted that in UNSCEAR reports prior to 1990–1994, the category "industrial uses" included a component reflecting "educational uses", which tended to distort the data. Since then, educational uses have been dealt with in a separate category, and the industrial data for earlier years have been adjusted to remove the educational component. For military activities, the average individual and collective doses both fell by a factor of about 10 over the whole period, from 1.3 mSv to 0.1 mSv and from 420 man Sv to about 50 man Sv, respectively.

737. The estimates of occupational radiation exposure in this annex have benefited from a much more extensive and complete database than was previously available to the Committee. The efforts by countries to record and improve dosimetric data were reflected in the responses to the UNSCEAR Global Survey of Occupational Radiation Exposures and the UNSCEAR Global Survey of Medical Radiation Usage and Exposures and have led to improved estimates and understanding of occupational exposures. However, the Committee considers that further guidance on these matters would help improve the quality of its assessments.

738. The Committee's current estimate of the worldwide collective effective dose due to occupational exposure from man-made sources is 4,430 man Sv (about 800 man Sv to workers in the nuclear fuel cycle, about 3,540 man Sv to workers in medical uses and about 400 man Sv to workers in industrial uses, military activities and miscellaneous activities). This estimate is about the same as that made by the Committee for the late 1970s. This is because, for the latest period, the evaluation of occupational exposure in the medical field is more reliable, and it contributes about 75% of the collective dose. The figure for occupational exposure from man-made sources has changed greatly since 1970, when occupational exposure was dominated by the practices in the nuclear fuel cycle. Except for medical uses, all other practices have shown a reduction in the level of exposure. A significant part of the reduction comes from the nuclear fuel cycle, particularly from uranium mining. However, reductions are seen in all the main

categories: industrial uses, medical uses, military activities and miscellaneous uses. This trend is also reflected in the worldwide average annual effective dose due to occupational exposure, which has fallen from about 1.7 mSv to 0.5 mSv (table 92).

739. No attempt has been made to deduce any trends in the estimates of dose for occupational exposure to natural sources of radiation, because the supporting data are somewhat limited. The UNSCEAR 1988 Report [U7] made a crude estimate of about 20,000 man Sv for this source, which was subsequently revised downward to 8,600 man Sv in the UNSCEAR 1993 Report [U6]. The UNSCEAR 2000 Report [U3] estimated a value of 11,700 man Sv, of which 6,000 man Sv was due to elevated levels of radon and its progeny in workplaces other than mines, 5,700 man Sv to extraction and processing activities, and 800 man Sv to the exposure of aircrew to cosmic radiation. In the current report, the estimate for the collective dose has risen to 37,260 man Sv, the largest contribution coming from mining operations—16,560 man Sv from coal mining and 13,800 man Sv from other mining. About 6,000 man Sv is due to exposure to radon and its progeny in workplaces other than mines, and 900 man Sv is due to the exposure of aircrew to cosmic radiation. The estimate is still considered to be crude, although the data on occupational exposure in Chinese coal mines have reduced some of the uncertainty in this estimate. The main contributor to the average collective dose is coal mining. On the basis of the data presented in the literature, the level of exposure may be declining, since the average effective dose decreased by a factor of 2 for workers in the Chinese coal mines [T4]. According to the literature, the level of exposure has decreased in nine European countries, while the average collective dose and average effective dose decreased by a factor of almost 2 from 1996 to 2000 [F15].

740. The doses for each practice for the year 2007 were projected on the basis of the trends for all countries. In general, the trend is for an increasing number of workers, and decreasing collective doses and effective doses for all the practices in the categories of medical and industrial uses of radiation, and also for the category of miscellaneous uses.

CONCLUSIONS ON PUBLIC AND WORKER EXPOSURE

741. Exposure to natural sources of radiation is an unavoidable fact of the human condition. The estimates of the global average per caput values of exposure to natural sources of radiation are essentially the same as in the UNSCEAR 2000 Report. The estimated value of worldwide average annual exposure to natural radiation sources remains at 2.4 mSv. The normal range of exposures to the various components is presented in table 12. The dose distribution worldwide is expected to follow approximately a log-normal distribution, and most annual exposures would be expected to fall in the range 1–13 mSv.

742. The values for occupational exposure for the periods 1995–1999 and 2000–2002 have changed greatly compared with those in the UNSCEAR 2000 Report. The collective effective dose resulting from exposures to natural sources (in excess of the average levels of natural background) is estimated to be about 37,260 man Sv, about three times higher than the value estimated in the UNSCEAR 2000 Report [U3]. The largest component of this, 30,360 man Sv, comes from mining (16,560 man Sv due to coal mining and 13,800 man Sv due to other mining operations, excluding uranium mining); 6,000 man Sv is due to "workplaces other than mines" and 900 man Sv is due to the exposure of aircrew to cosmic radiation. The large difference with respect to the UNSCEAR 2000 Report comes from the level of exposure in coal mines. For the current period, the estimate is based on an assessment of exposure in Chinese mines, which represents a very large number of workers. No matter how the estimates are made, the collective dose due to natural sources of radiation is associated with much greater uncertainty than that due to man-made sources of radiation. The trends are presented in table 92.

743. Residues due to conventional mining operations also give rise to very large quantities of material with enhanced levels of naturally occurring radionuclides; these represent a challenge regarding both the disposal of the residues and site restoration. The large diversity of ores containing low levels of nuclides from the uranium and thorium families, which may be concentrated in products, by-products and wastes, complicates the problem, and the detailed picture of worldwide exposure is far from complete. Although doses to the public are usually low, of the order of a few microsieverts or less, some exposed groups can receive doses in the millisievert range, which may deserve attention.

744. For all fuel cycle operations (mining and milling, reactor operation and fuel reprocessing), the local and regional exposures are estimated to be 0.72 man Sv/(GW a). For the present world nuclear energy generation of 278 GW a, the collective dose per year of practice is of the order of 200 man Sv. The collective doses due to globally dispersed radionuclides are delivered over very long periods; if the practice of nuclear power production is continued for 100 years at the present capacity, the maximum annual per caput effective dose to the global population would be less than 0.2 μSv. This dose rate is low compared with that due to natural background radiation.

745. The current estimate for the total collective dose to workers in practices using man-made sources of radiation has changed the figure of occupational exposure. The collective effective dose has in the past been dominated by practices in the nuclear fuel cycle, but the current estimate has shown that occupational exposure in the medical field has become dominant. The collective effective dose in practices

using man-made sources of radiation may be around 4,730 man Sv (about 800 man Sv to workers in the nuclear fuel cycle, about 3,540 man Sv to workers in medical uses, and about 400 man Sv to workers in industrial uses, military activities and miscellaneous uses). These figures have increased compared with the estimates in the UNSCEAR 2000 Report [U3]; the most important decrease was due to the nuclear fuel cycle. The trends are presented in table 92 and figure LXVII.

746. The main contribution to the global collective dose to the public due to man-made sources comes from the testing of nuclear weapons in the atmosphere in the period between 1945 and 1980. The estimated global average annual per caput effective dose reached a peak of 110 μSv in 1963 and has since decreased to about 5 μSv (mainly due to residual levels of ^{14}C, ^{90}Sr and ^{137}Cs in the environment). The average annual doses are higher than the global average by 10% in the northern hemisphere (where most of the testing took place) and are lower in the southern hemisphere.

747. In addition to areas related to atomic bomb production and testing, military uses of radiation have also left a legacy of numerous small contaminated sites across the planet. Efforts to decontaminate these sites and return them to public use have been a focus of attention in many countries. Exposures and collective doses are site-specific; once the areas are defined, exposures can be constrained and clean-up procedures implemented. In general, site release criteria consider annual individual doses for a hypothetical critical group of people in the range 0.3–1.0 mSv. Average local and regional annual individual doses will be at least one order of magnitude lower, and the contribution to the worldwide population doses will most probably be negligible.

TABLES

Tables available as MS Excel workbooks on the attached CD-ROM

Public.xls

A-1 Natural radionuclide content of soil

A-2 Activity concentration in building materials

A-3 Activity concentration of naturally occurring radionuclides in drinking water (mBq/L)

A-4 Nuclear power plants operating in the period 1998–2002

A-5 Energy generated by nuclear power plants in the period 1998–2002 (GW a)

A-6 Noble gases released from nuclear power plants in airborne effluents (GBq)

A-7 Tritium released from nuclear power plants in airborne effluents (GBq)

A-8 Iodine-131 released from nuclear power plants in airborne effluents (GBq)

A-9 Carbon-14 released from nuclear power plants in airborne effluents (GBq)

A-10 Particulates released from nuclear power plants in airborne effluents (GBq)

A-11 Tritium released from nuclear power plants in liquid effluents (GBq)

A-12 Other radionuclides released from nuclear power plants in liquid effluents (GBq)

A-13 Releases from nuclear fuel cycle reprocessing plants in airborne effluents (GBq)

A-14 Releases from nuclear fuel cycle reprocessing plants in liquid effluents (GBq)

Workers.xls

A-15 Dose monitoring and recording procedures for occupational exposure

A-16 Exposures to workers from natural sources of radiation

A-17 Exposures to workers from uranium mining

A-18 Exposures to workers from uranium milling

A-19 Exposures to workers from uranium enrichment and conversion

A-20 Exposures to workers from fuel fabrication

A-21 Exposures to workers at nuclear power reactors

A-22 Exposures to workers from fuel reprocessing

A-23 Exposures to workers from research related to the nuclear fuel cycle

A-24 Exposures to workers from medical uses of radiation

A-25 Exposures to workers from diagnostic radiology

A-26 Exposures to workers from nuclear medicine according to job category

A-27 Exposures to workers from all medical uses of radiation

A-28 Exposures to workers from various industrial uses of radiation

A-29 Exposures to workers from all industrial uses of radiation

A-30 Exposures to workers from miscellaneous uses of radiation

A-31 Exposures to workers from military activities

Table 1. Dose conversion factors and dose conversion coefficients for natural radionuclides [U3]

Radionuclide	*Dose conversion factor[a], DCF_{soil} ((nGy/h)/(Bq/kg))*	
^{40}K	0.041 7	
^{238}U series	0.462	
^{232}Th series	0.604	
Radionuclide	*Dose conversion coefficient[b] (Sv/Bq)*	
	Inhalation, $e_{inh}(50)$	*Ingestion, $e_{ing}(50)$*
^{238}U	2.9×10^{-6}	4.5×10^{-8}
^{234}U	3.5×10^{-6}	4.9×10^{-8}
^{230}Th	1.4×10^{-5}	2.1×10^{-7}
^{226}Ra	3.5×10^{-6}	2.8×10^{-7}
^{210}Pb	1.1×10^{-6}	6.9×10^{-7}
^{210}Po	3.3×10^{-6}	1.2×10^{-6}
^{232}Th	2.5×10^{-5}	2.3×10^{-7}
^{228}Ra	2.6×10^{-6}	6.9×10^{-7}
^{228}Th	4.0×10^{-5}	7.2×10^{-8}
^{235}U	3.1×10^{-6}	4.7×10^{-8}

[a] External dose rates due to radionuclides in soil.
[b] Effective dose per unit intake due to internal exposure for adults.

Table 2. Collective effective dose per unit release of radionuclides from nuclear reactors [U3]

Type of release	*Radionuclide*	*Reactor type[a]*	*Pathway*	*Collective dose per unit release (man Sv/PBq)*
Airborne	Noble gases	PWR, LWGR, FBR, HWR	Immersion	0.11
		BWR	Immersion	0.43
		GCR	Immersion	0.9
	^{3}H	All	Ingestion	2.1
	^{14}C	All	Ingestion	270
	^{131}I	All	External	4.5
			Ingestion	250
			Inhalation	49
	Particulate	All	External	1 080
			Ingestion	830
			Inhalation	33
Liquid	^{3}H	All	Ingestion/ inhalation	0.65
	Other	All	Ingestion	330

[a] PWR: pressurized water reactor; LWGR: light-water-cooled, graphite-moderated reactor; FBR: fast breeder reactor; HWR: heavy-water-cooled and -moderated reactor; BWR: boiling water reactor; GCR: gas-cooled, graphite moderated reactor.

Table 3. Collective effective dose per unit release of radionuclides from fuel reprocessing plants [U3]

Type of release	*Radionuclide*	*Collective dose per unit release (man Sv/PBq)*
Airborne	^{3}H	2.1
	^{14}C	270
	^{85}Kr	0.007 4
	^{129}I	0.044
	^{131}I	0.000 3
	^{137}Cs	0.007 4
Liquid	^{3}H	0.001 4
	^{14}C	1 000
	^{90}Sr	4.7
	^{106}Ru	3.3
	^{129}I	99
	^{137}Cs	98

Table 4. Population distribution of cosmic ray dose rates outdoors at sea level [U3]

Latitude (degrees)	*Population in latitude band (%)*		*Effective dose rate (nSv/h)*	
	Northern hemisphere	*Southern hemisphere*	*Directly ionizing component*	*Neutron component*
80–90	0	0	32	11
70–80	0	0	32	11
60–70	0.4	0	32	10.9
50–60	13.7	0.5	32	10
40–50	15.5	0.9	32	7.8
30–40	20.4	13.0	32	5.3
20–30	32.7	14.9	30	4
10–20	11.0	16.7	30	3.7
0–10	6.3	54.0	30	3.6
Total	100	100		
Population-weighted average				
Northern hemisphere			31.0	5.6
Southern hemisphere			30.3	4.0
World			30.9	5.5

Table 5. Population-weighted average annual effective doses (mSv) due to cosmic radiation [U3]

Conditions	*Directly ionizing component*			*Neutron component*			*Total*
	Northern hemisphere	*Southern hemisphere*	*World*	*Northern hemisphere*	*Southern hemisphere*	*World*	*World*
Outdoors, at sea level	0.27	0.27	0.27	0.05	0.04	0.05	0.32
Outdoors, adjusted for altitude	0.34	0.33	0.34	0.12	0.09	0.12	0.46
Adjusted for altitude, shielding and occupancy	0.29	0.28	0.28	0.10	0.07	0.10	0.38

Table 6. Absorbed dose rates in air (nGy/h)

Data not referenced are from the UNSCEAR Global Survey on Exposures to Natural Radiation Sources

Region/country	*Population (10^6)* [C17]	*Outdoors*						*Indoors*					
		Cosmic radiation		*Terrestrial radiation*		*Total*		*Cosmic radiation*		*Terrestrial radiation*		*Total*	
		Mean	*Range*	*Mean*	*Range*	*Mean*	*Range*	*Mean*	*Range*	*Mean*	*Range*	*Mean*	*Range*
Africa													
Libyan Arab Jamahiriya	5.9	28	25–31	23	18–24	51	48–54						
Mauritius	1.24					98	80–126					105	80–126
Tanzania (United Rep. of) [B6]	37.4					104	98–121						
North America													
Canada	33.1			24	11–44	54	31–75						
Mexico	107					88.3	23–184					105	37–217
Central America													
Costa Rica [M25, M30]	5.5	36	29.3–80.2	29.9	5.6–66.6	65.9	35–147					151	85–191
Cuba [T6, T7]	11.4	34	32–67	24	4–162	55	38–196	27	26–54	30	10–76	44	37–103
East Asia													
Azerbaijan	8	37	30–45	102	45–160	140	75–205	21	16–26	123	87–160	144	103–186
Bangladesh [A4, A5, A6, H24, U40]	147			120	44–245					156	57–319		
China [C11, Z4]	1 313			69.9	12.7–1 300	81.5	11.6–523					124.1	1.12–174.1
—Taiwan [L11, L12]	23	27	25.7–58	52	24–68	79		24	23–52	101	66–189	125	
India [N2]	1 095			41.5									
Indonesia	245	27.5	21.1–61.9	40	23.9–40.1	67.5	45–102						
Japan [A2, F4]	124.76	35.3	30.1–59.4									78.3	52.4–106.5
Kazakhstan	15.2				60–500						150–280		
Korea, Rep. of [K16]	48.8					79	18–200						
Pakistan [B50]	166			59	1.0–97								
Philippines	75.9	21		24		45							

Region/country	*Population (10^6)* [C17]	*Outdoors*						*Indoors*					
		Cosmic radiation		*Terrestrial radiation*		*Total*		*Cosmic radiation*		*Terrestrial radiation*		*Total*	
		Mean	*Range*	*Mean*	*Range*	*Mean*	*Range*	*Mean*	*Range*	*Mean*	*Range*	*Mean*	*Range*
West Asia													
Armenia	2.98												
Islamic Republic of Iran	68.7	40.5	33.0–57.6	71	36–130	111.5	69–187.6	16.8	13.2–31.3	115	70–165	131.8	83.2–196.3
Kuwait	2.4	35		52		87		29		90		119	
Turkey [K2]	70.4	15.7	8.4–35.6	48.8	15–80	65	32–94						
North Europe													
Denmark [A1, N14, S36, U42]	5.5	31		35	25–70	66	56–101	31		54	19–259	85	50–290
Finland [A19, A20]	5.2	32		71	45–139	103	77–171	32		73	24–181	105	56–213
Iceland [E4]		31		40	4–83	71		25		23	14–32	48	
Lithuania [L3]	3.45	33	32–35	62	46–82	95	79–115	26	26–28	81	34–224	107	53–250
Sweden[a,b] [M27, M29, S15]	9	33	32–50	64	10–580	97	40–630	36	17–75	98	10–1 250	120	20–1 300
West Europe													
Belgium [G10]	10.4	33[a]	32–36	43	13–80	76	45–120	26	20–36	60	32–180	86	55–200
Germany	82.4	32		57		89				80	20–700		
Ireland [C24, M9, M15, M16]	3.84	33		32	2–110	65	35–143	26		62	10–140	94	43–168
Italy [B29, C4]		38	32–54	74	11–209	112	57–243	31	26–43	105	0–690	136	29–717
Liechtenstein	0.03	38		34.6		72.6							
Luxembourg	0.22	32		49	14–73	81							
Spain [Q1, Q2, Q6, S42, S43]	40.4	34.6	30.8–41.0	50.4	19–88	85	50–129	22.1	19.7–26.2	73.1	40–124	95.2	60–151
Switzerland [L22]	7.5	39	34–68	42	14–118	81	53–155	31	27–54			100	55–215

Region/country	*Population (10^6)* [C17]	*Outdoors*						*Indoors*					
		Cosmic radiation		*Terrestrial radiation*		*Total*		*Cosmic radiation*		*Terrestrial radiation*		*Total*	
		Mean	*Range*	*Mean*	*Range*	*Mean*	*Range*	*Mean*	*Range*	*Mean*	*Range*	*Mean*	*Range*
East Europe													
Bulgaria	7.4	30	27–42	70	48–96	100	75–140	25	22–35	75	57–93	100	80–130
Czech Republic [M18]	10.2	34	32–62	66	6–245	100	40–285	34[c]		85	42–2 000[d]	119	74–2 000
Poland [B24, B25]	38.15	33.5	31.3–60.8	47.4	18.8–86.0	80.9	51.0–126.2					93.8	54.7–193.8
Romania [B1, B2, C20, C21, C22, I1]	21.3	33	32–38	59	20–125	92	52–163	27	26–30	83	30–170	110	56–200
Slovenia [A18]	2.0	32	30–47	56	4–147					75	40–250		
South Europe													
Albania [I4]	3.6					94	77.2–103						
Croatia	4.5					115	70–140						
Greece [C18, C19, P14, S5]	10.7			31	17–88					36	20–101		
Montenegro	0.63			63	28–150								
Oceania													
New Zealand	4.1	32[a]		44	2–90	76	34–122	32[c]		23	0–77	55	32–109

[a] Ionizing component.
[b] Average values refer to population-weighted mean.
[c] Assumed same as outdoor.
[d] Excluding area in Jachymov contaminated with naturally occurring radioactive material.

Table 7. Distribution of population with respect to the outdoor absorbed dose rate in air due to terrestrial gamma radiation

Data not referenced are from the UNSCEAR Global Survey on Exposures to Natural Radiation Sources

Region/country	*Population (10^6)*	*Population (10^3) residing in areas with various levels of outdoor absorbed dose rate in air (nGy/h)*											
		<20	*20–29*	*30–39*	*40–49*	*50–59*	*60–69*	*70–79*	*80–89*	*90–99*	*100–199*	*200–299*	*>300*
Africa													
Libyan Arab Jamahiriya	1.50	1 500											
Central America													
Costa Rica	5.5	605	918.5	605	2 926	412.5		27.5					
Cuba	11.20	6 000	5 000	200	2	<1							
East Asia													
Bangladesh	57.08				1 200	1 510	12 001	4 780	10 970	2 921	16 810	6 890	
China	1 282.35	94 884			232 426	364 745	279 327	122 493	75 404	36 074	75 011	1 984	
Indonesia	213.68	48 203	31 975	35 616	17 301	3 929	2 968	1 431	620	3 096	10 252	832	
Japan [U3]	124.76		9 619	26 463	20 561	23 382	39 546	5 193					
Korea, Rep. of [U3]	44.61	1 760	3 096	9 605	4 097	2 220	1 724	4 421	4 421	2 211	11 053		
Malaysia [U3]	19.64					984	213	1 214	2 498	8 487	6 248		
Philippines	75.90	26 775	27 922	14 535	4 284	1 377	688.5	275.4	45.90				
West Asia													
Azerbaijan	8.00	6 000	1 500	500									
Islamic Republic of Iran	63.76			3 188	1 402.72	16 832.64	12 050.64	24 356.32	2 550.4	318.8	3 060.48		
North Europe													
Denmark [A17]	5.20		250	2 100	2 200	600	50						
Estonia [U3]	1.47	6	5	25	149	314	367	592	9				
Iceland [E4, T3]	0.30			150	150								
Finland [A19, A20, C5]	5.20					922	1 143	2 633	174	328			
Lithuania [G14]	3.45				816	606	1 386	188	455				
Sweden [S15, S45]	8.88	214	396	798	1 135	1 370	1 289	1 094	1 024	840	564	2	0.2

Region/country	*Population (10^6)*	*Population (10^3) residing in areas with various levels of outdoor absorbed dose rate in air (nGy/h)*											
		<20	*20–29*	*30–39*	*40–49*	*50–59*	*60–69*	*70–79*	*80–89*	*90–99*	*100–199*	*200–299*	*>300*
West Europe													
Belgium [G10]	10.22	300	2 200	2 400	2 600	2 500	200	20					
Germany [U3]	81.10	700	8 600	10 000	20 900	28 000	9 600	1 500	800	700	300		
Ireland [C6, M9]	3.84	298	787	1 148	992	251	7	41	0	0	2		
Italy [B29, B31, C4]	57.30	125		50	5 600	28 050	8 100	1 950	250	3 550	6 500	3 125	0
Luxembourg	0.45	31.9	14.3	57.2	250.2	90.2	4.4						
Netherlands [U3]	15.58	3 459	5 484	2 353	2 976	1 262	47						
Switzerland	6.71	60	620	1 100	3 900	570	70	160	70	60	100		
United Kingdom [U3]	54.00	6 000	12 000	30 000	6 000								
East Europe													
Bulgaria	9.41				170	357	4 756	1 130	214	1 472			
Czech Rep. [M7]	10.30	3	89	262	605	1 898	4 342	1 846	829	252	177		
Hungary [U3]	10.14	163	479	836	1 017	1 316	3 488	1 163	765	367	530		17
Poland	38.12	426	3 219	13 097	15 528	4 208	1 193	419	30				
Romania [I1]	21.83		293.1	1 309.1	4 149.2	6 404.2	5 096.3	3 878.6	721.6	562.8	45.1		
Russian Fed. [U3]	148.10	450		460	7 150	22 800	84 470	5 730	17 800	5 330	3 910		
Slovakia [U3]	5.29		22	192	721	1 364	1 292	868	498	243	85		
South Europe													
Albania [U3]	3.50		50	50	100	100	500	2 000	300	200	100	50	50
Greece	10.36			1 160	5 605	1 067	1 250	572	147	225	231	50	50
Montenegro	0.60	31	45	155	117	173			80				
Portugal [U3]	9.43	333	444	1 814	606	1 325	653	313	582	417	2 352	594	
Spain	40.84			1 198	5 644	5 181	10 403	2 871	912	2 424	8 477		

Region/country	*Population (10^6)*	*Population (10^3) residing in areas with various levels of outdoor absorbed dose rate in air (nGy/h)*											
		<20	*20–29*	*30–39*	*40–49*	*50–59*	*60–69*	*70–79*	*80–89*	*90–99*	*100–199*	*200–299*	*>300*
Oceania													
New Zealand	3.80	1 570	1 390	600	200	40	<10						
Total													
Total		136 641	148 346	193 504	373 330	526 162	488 173	193 160	122 170	66 983	145 808	13 527	117
Fraction of total		0.056 7	0.061 6	0.080 4	0.155 0	0.218 5	0.202 7	0.080 2	0.050 7	0.027 8	0.060 6	0.005 6	0.000 1
Cumulative fraction		0.056 7	0.118 4	0.198 7	0.353 8	0.572 3	0.775 0	0.855 2	0.906 0	0.933 8	0.994 3	0.999 9	1.000 0

Table 8. Reference annual intake of air, food and water [U3]

Intake	*Infants (1 year)*	*Children (10 years)*	*Adults*
Breathing rate (m^3/a)			
Air	1 900	5 600	7 300
Food consumption rate (kg/a)			
Milk products	120	110	105
Meat products	15	35	50
Grain products	45	90	140
Leafy vegetables	20	40	60
Roots and fruits	60	110	170
Fish products	5	10	15
Water and beverages	150	350	500

Table 9. Reference values for concentration of radionuclides of the uranium and thorium series in human tissues (mBq/kg) [U3]

Radionuclide	*Lung*	*Liver*	*Kidney*	*Muscle and other tissues*	*Bone*
^{238}U	20	3	30	5	100
^{230}Th	20	9	5	1	20–70
^{226}Ra	4.1	4.1	4.1	4.1	260
^{210}Pb	200	400	200	100	3 000
^{210}Po	200	600	600	100	2 400
^{232}Th	20	3	3	1	6–24
^{228}Ra	20	3	2	2	100

Table 10. Examples of areas of high natural radiation background

Data not referenced are from the UNSCEAR Global Survey on Exposures to Natural Radiation Sources

Region/country	*Area*	*Reference*	*Soil concentration (Bq/kg)*				*Exposure rate in air (nGy/h)*		*^{222}Rn (Bq/m^3)*		*^{222}Rn (Bq/L)*
			^{40}K	*^{238}U*	*^{226}Ra*	*^{232}Th*	*Outdoors*	*Indoors*	*Outdoors*	*Indoors*	*Water*
High cosmic radiation											
China	Ganzu[a]	[Z1]					73				
China	Qinghai[a]	[S16, Z1]					95 (65–127)				
China	Sichuan[a]	[Z2]					82				
China	Tibet[a]	[S16, Z1]					121 (80–140)				
United States	Denver, Colorado	[S26]					196				
Uranium areas											
Brazil	Araxá	[V18]					2 800				
Brazil	Caetité	[B27]							69	82	
Brazil	R.G. Norte	[M3, M4]	941		50	69	108 (54–253)			4–140	
Brazil	Phosphate area, PE	[A15, M4]		38–300	29–207						
United States	Reading Prong, New Jersey	[S27]						170			
Uranium and thorium areas (volcanic intrusive)											
Brazil	Pocos de Caldas, MG, urban areas	[S2]					145 (93–244)				
Brazil	Pocos de Caldas, MG, rural areas	[V18]					280 (130–1 500)	200 (130–340)	130 (56–280)	204 (50–1 046)	
Czech Republic	Central Bohemia, Pluton middle area	[M7]	988–1 599	68–220	76–275	74–159	90–170	119	2–25	442 (10–20 870)	
Italy	Lazio	[B29, B32]					175 (120–270)	250 (105–440)		119 (26–1 036)	
Italy	Campania	[B29, B32]					198 (141–243)	310 (115–720)		95 (13–172)	
Italy	Orvieto	[U3]					560				
Italy	Southern Tuscany	[B30]					150–300	190 (40–350)		200 (30–1 240)	
Niue Island	Pacific	[S27]					Max. 1 100				
Romania	Crucea and Grinties	[B38]	486	57		31					

Region/country	*Area*	*Reference*	*Soil concentration (Bq/kg)*				*Exposure rate in air (nGy/h)*		*^{222}Rn (Bq/m^3)*		*^{222}Rn (Bq/L)*
			^{40}K	*^{238}U*	*^{226}Ra*	*^{232}Th*	*Outdoors*	*Indoors*	*Outdoors*	*Indoors*	*Water*
Monazite sand coastal areas											
Brazil	Guarapari and Meaipe, ES	[S2]					84 (26–300)[b]				
China	Yangjiang, Quangdong	[S27]					370				
Egypt	Roseta coastal area	[S27]					20–400				
India	Kerala and Madras	[G3, N1]					1 500 (845–5 270)				
Thermal waters											
Austria	Bad Gastein	[S27]									1 480
China	Sichuan, Jiangzha	[X1]					256–9 140		(22–22 000	68 000–340 000	
Hungary	Mount Gellért	[S27]									Up to 7.15
India	Tuwa	[S27]									4–40
Indonesia	West Java	[S27]	48–252		2.4–422	0.5–66	97 (33–224)				45–83
Islamic Republic of Iran	Ramsar	[M32, S27]	300–945		80–50 000	15–47	765 (80–100 000)	1 153 (100–105 000)	65 (0–500)	2 745 (55–31 000)	64 (1–160)
Islamic Republic of Iran	Mahallat	[S26, S27]	364–873		500–7 300	15–41	300–3 800		30 (6–200)	600 (55–1 000)	710 (145–2 730)
Japan	Misasa	[S27]									437
Slovenia	Podcetrtek	[S27]									1–63
Slovenia	Spas	[V13]						60–154		15–279	
Others											
Azerbaijan			800–1 000	100–7 000	500–2 500	100–1 000	877–8 770				
China	Cave dwellings, Ganzu	[S16, Y1]								21–3 660	
China	Cave dwellings, Yanan	[W12]								32–278	
Indonesia	Bangka Island						330 (90–540)			167 (max. 416)	
Indonesia	Karimu Island						310 (200–410)				
Philippines	San Vicente						300 (75–1 558)				
Russian Federation	Yssyk-Kul (Kyrgyzstan)	[Z3]			100–150	10–160	Up to 300			162–352	

Region/country	Area	Reference	Soil concentration (Bq/kg)				Exposure rate in air (nGy/h)		^{222}Rn (Bq/m^3)		^{222}Rn (Bq/L)
			^{40}K	^{238}U	^{226}Ra	^{232}Th	Outdoors	Indoors	Outdoors	Indoors	Water
Spain	Galicia South, Arribes del Duero, Sierra de Guadarrama, Campo de Arañuelo	[M11, Q6, Q8]	810–1 240		60–250	42–71	136–260	197–377	10–210	150–1 400	
Switzerland	Tessin, Alps, Jura	[S27]					100–200				
United Kingdom	Kerrier district, south-west peninsular	[W1]								<2–17 000	
United Kingdom	South Wales caves	[F16]								max. 3 094	
World average for natural background radiation											
UNSCEAR 2000 Report		[U3]	420	33	32	45	59	84		39	

a External exposure not including neutrons.
b Kerma rates of up to 5 460 nGy/h can be measured at localized spots [S2].

Table 11. High-background areas: distribution of population with respect to total effective dose
Data from the UNSCEAR Global Survey on Exposures to Natural Radiation Sources

Region/country	Area	Distribution of population (10^3) residing in high-background areas with various levels of total effective dose (mSv/a)										
		3.0–3.49	3.50–3.99	4.0–4.49	4.5–4.99	5.0–5.99	6.0–6.99	7.0–7.99	8.0–8.99	9.0–9.99	>10	Population (10^3)
West Asia												
Islamic Republic of Iran [S28]	Ramsar	110	125	120	140	20	10	23	31	20	200	799
East Europe												
Czech Republic [M7]	Central Bohemian Pluton	41	39	32	31	49	36	28	20	15	54	345
	Central Bohemian Pluton	2	3	3	3	6	6	5	5	4	28	65
	Central Moldanubian Pluton	36	29	21	18	25	16	11	7	5	12	180
	Trebic Massif	22	21	18	17	27	20	15	11	8	29	188
	Krkonose-Jizera Pluton	59	44	30	24	31	18	12	7	5	11	241
	Carlsbad Pluton	48	37	25	21	27	17	11	7	4	11	208
West Europe												
Spain	Galicia South, Arribes del Duero, Sierra de Guadarrama, Campo de Arañuelo	40	800				1 000				20	1 860

Table 12. Public exposure to natural radiation

Source of exposure		*Annual effective dose (mSv)*	
		Average	*Typical range*
Cosmic radiation	Directly ionizing and photon component	0.28	
	Neutron component	0.10	
	Cosmogenic radionuclides	0.01	
	Total cosmic and cosmogenic	0.39	0.3–1.0[a]
External terrestrial radiation	Outdoors	0.07	
	Indoors	0.41	
	Total external terrestrial radiation	0.48	0.3–1.0[b]
Inhalation	Uranium and thorium series	0.006	
	Radon (^{222}Rn)	1.15	
	Thoron (^{220}Rn)	0.1	
	Total inhalation exposure	1.26	0.2–10[c]
Ingestion	^{40}K	0.17	
	Uranium and thorium series	0.12	
	Total ingestion exposure	0.29	0.2–1.0[d]
Total		2.4	1.0–13

[a] Range from sea level to high ground elevation.
[b] Depending on radionuclide composition of soil and building material.
[c] Depending on indoor accumulation of radon gas.
[d] Depending on radionuclide composition of foods and drinking water.

Table 13. Doses to members of the public due to the industrial release of NORM in the United Kingdom [W6]

Industry	*Discharge route*	*Pathway*	*Annual dose (μSv)*	
			Critical group	*General public*
Coal-fired power station	Atmospheric releases via stack	All	1.5	0.1
	Building material made from ash	Radon inhalation	600	
		External	900	
Oil and gas extraction	Authorized discharges to sea, and scales	Ingestion of seafood and external exposure due to fishing gear	<30	
Gas-fired power station	Atmospheric releases via stack	All	0.75	0.032
Steel production	Atmospheric releases via stack	All	<100	<2
	Building material made from slag	Radon inhalation	550	
		External	800	
Zircon sands	Atmospheric releases via stack	Inhalation	<1	<1

Table 14. Worldwide uranium production [O16, O17, O21, W8]

Country	*Annual production (t)*						*Cumulative production (t)*
	1998	*1999*	*2000*	*2001*	*2002*	*2003*	*Total to 2003*
Argentina	7	4	0	0	0	0	2 631
Australia	4 894	5 984	7 579	7 720	6 854	7 573	113 304
Belgium	15[a]	0	0	0	0	0	680[a]
Brazil	0	0	80	56	272	230	1 645
Bulgaria	0	0	0	0	0	0	16 735
Canada	10 922	8 214	10 683	12 522	11 607	10 455	374 548
China	590[b]	700[b]	700[b]	700[b]	730[b]	730[b]	27 689[b,c]
Congo, D.R.	0	0	0	0	0	0	25 600
Czech Republic	610	612	507	456	465	452	108 649[d]
Finland	0	0	0	0	0	0	30
France	452	416	296	184	18[e]	9	75 965
Gabon	725	0	0	0	0	0	25 403
Germany	30	29	28	27[e]	221[e]	150[e]	219 239
Hungary	10	10	10	10	10	4	21 080
India	207[f]	207[f]	207[f]	230[f]	230[f]	230[f]	7 963[f]
Japan	0	0	0	0	0	0	84
Kazakhstan[g]	1 270	1 560	1 870	2 114	2 822	3 327	24 639
Madagascar	0	0	0	0	0	0	785
Mexico	0	0	0	0	0	0	49
Mongolia	0	0	0	0	0	0	535
Namibia	2 780	2 690	2 715	2 239	2 333	2 037	78 794
Niger	3 714	2 907	2 911	2 919	3 080	3 157	91 186
Pakistan	23[f]	23[f]	23[f]	46[f]	38[f]	40[f]	931[f]
Poland	0	0	0	0	0	0	660
Portugal	19	10	14	4	0	0	3 680
Romania	132	89	86	85[e]	90[e]	90[e]	17 989[e]
Russian Federation[g]	2 530	2 610[f]	2 760[f]	3 090[f]	2 850[f]	3 073[f]	32 136
South Africa	965[h]	927[h]	838[h]	878[h]	828[h]	747[h]	157 618[h]
Spain	255	255	255	30[e]	37[e]	0	6 156
Sweden	0	0	0	0	0	0	91
Ukraine[g]	1 000	1 000	1 000	750[f]	800[f]	800[f]	9 900[f,g]
United States	1 810	1 773	1 522[f]	1 015	902	769	356 485
Uzbekistan[g]	1 926	2 159	2 028	1 945	1 859	1 603	23 682
Zambia	0	0	0	0	0	0	102
World total	34 886	32 179	36 112	37 020	36 042	35 492	2 204 656[i]

a Produced from imported phosphates.
b Estimate for continental China.
c Production in China since 1990.
d Total production since 1946.
e Production resulting from decommissioning.
f Provisional data.
g Production since 1992.
h Uranium is by-product of gold mining.
i Includes 377 613 t of uranium produced in the former Soviet Union from 1945 to 1991, and 380 t produced in the former Yugoslavia before 1991.

Table 15. Worldwide installed capacity for fuel cycle installations [I35]

Country	*Conversion to UF_6 (t U/a)*	*Enrichment (10^3 SWU/a)*[a]	*Fuel fabrication (t/a)*[b]	*Reprocessing (t/a)*[b]
Argentina	62[c]	20[c]	150	
Belgium			435	
Brazil	40		280	
Canada	12 500		2 700	
China	1 500	1 000	400	
France	14 350	10 800	1 585	1 700
Germany		1 800	650	
India			594	
Japan		1 050	1 689	120
Korea, Rep. of			800	
Netherlands		2 500		
Pakistan		5	20	
Romania			110	
Russian Federation	30 000	15 000	2 600	400
Spain			400	
Sweden			600	
United Kingdom	6 000	2 300	1 680	2 700
United States	14 000	11 300	3 450	
Total	78 452	45 775	18 143	4 920

[a] SWU: separative work unit. The SWU is a complex unit that is a function of the amount of uranium processed, the degree to which it is enriched and the level of depletion of the remainder. It is indicative of the energy used in enrichment when feed and product quantities are expressed in kilograms.
[b] Tonnes of heavy metal.
[c] Design capacity.

Table 16. Electrical energy generated (GW)

Reactor type	*1998*	*1999*	*2000*	*2001*	*2002*	*Average 1998–2002*
AGR	6.52	6.39	6.14	6.26	0.33	5.13
BWR	64.06	66.86	67.32	69.09	64.77	66.42
FBR	0.28	0.43	0.41	0.44	0.43	0.40
GCR[a]	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
LWGR	7.29	8.14	8.30	7.87	8.06	7.93
HWR	11.35	12.17	12.56	13.71	13.66	12.69
PWR	154.27	158.19	164.59	167.09	170.91	163.10
WWER	20.46	20.62	22.52	23.58	25.62	22.56
All	264.23	272.80	281.84	288.05	283.79	278.23

[a] n.a. = not available.

Table 17. Historical values for normalized releases of radionuclides from nuclear reactors (TBq/(GW a))

Period	*PWR*[a]	*BWR*	*GCR*[b]	*HWR*	*LWGR*	*FBR*	*Total*[c]
Noble gases							
1970–1974	530	44 000	580	4 800	5 000[d]	150[d]	13 000
1975–1979	430	8 800	3 200	460	5 000[d]	150[d]	3 300
1980–1984	220	2 200	2 300	210	5 500	150[d]	1 200
1985–1989	81	290	2 100	190	2 000	820	330
1990–1994	27	354	2 050	2 100	1 700	380	330
1995–1997	13	180	252	250	460	210	130
1998–2002	11	44	28	80	3 156	36	112
Tritium							
1970–1974	5.4	1.8	9.9	680	26[d]	96[d]	448
1975–1979	7.8	3.4	7.6	540	26[d]	96[d]	38
1980–1984	5.9	3.4	5.4	670	26[d]	96[d]	44
1985–1989	2.7	2.1	8.1	690	26[d]	44	40
1990–1994	2.3	0.94	4.7	650	26[d]	49	36
1995–1997	2.4	0.86	3.9	330	26	49[d]	16
1998–2002	2.1	1.6	3.3	874	26[d]	49[d]	43
Iodine-131							
1970–1974	0.003 3	0.15	0.001 4[d]	0.001 4	0.08[d]	0.003 3[d]	0.047
1975–1979	0.005	0.41	0.001 4[d]	0.003 1	0.08[d]	0.005[d]	0.12
1980–1984	0.001 8	0.093	0.001 4	0.000 2	0.08	0.001 8[d]	0.03
1985–1989	0.000 9	0.001 8	0.001 4	0.000 2	0.014	0.000 9[d]	0.002
1990–1994	0.000 33	0.000 8	0.001 4	0.000 4	0.007	0.000 3[d]	0.000 7
1995–1997	0.000 2	0.000 3	0.000 4	0.000 1	0.007	0.000 2	0.000 4
1998–2002	0.000 3	0.000 6	0.000 07	0.000 1	0.009 9	0.000 2[d]	0.000 6
Carbon-14							
1970–1974	0.22[d]	0.52[d]	0.22[d]	6.3[d]	1.3[d]	0.12[d]	0.71
1975–1979	0.22	0.52	0.22[d]	6.3[d]	1.3[d]	0.12[d]	0.70
1980–1984	0.35	0.33	0.35[d]	6.3	1.3[d]	0.12[d]	0.74
1985–1989	0.12	0.45	0.54	4.8	1.3	0.12[d]	0.53
1990–1994	0.22	0.51	1.4	1.6	1.3[d]	0.12[d]	0.44
1995–1997	—	—	—	—	—	—	—
1998–2002	0.22	0.53	1.3	1.2	1.3[d]	0.12[d]	0.39
Particulates							
1970–1974	0.018	0.04	0.001[d]	0.000 04[d]	0.015[d]	0.000 2[d]	0.019
1975–1979	0.002 2	0.053	0.001	0.000 04	0.015[d]	0.000 2[d]	0.017
1980–1984	0.004 5	0.043	0.001 4	0.000 04	0.016	0.000 2[d]	0.014
1985–1989	0.002	0.009 1	0.000 7	0.000 2	0.012	0.000 2	0.004
1990–1994	0.000 2	0.18	0.000 3	0.000 05	0.014	0.012	0.04
1995–1997	0.000 1	0.35	0.000 2	0.000 05	0.008	0.001	0.085
1998–2002	0.000 03	0.049	0.000 2[d]	0.000 03	0.002 7	0.000 1	0.012

Period	*PWR*[a]	*BWR*	*GCR*[b]	*HWR*	*LWGR*	*FBR*	*Total*[c]
Tritium (liquid)							
1970–1974	11	3.9	9.9	180	11[d]	2.9[d]	19
1975–1979	38	1.4	25	350	11[d]	2.9[d]	42
1980–1984	27	2.1	96	290	11[d]	2.9[d]	38
1985–1989	25	0.78	120	380	11[d]	0.4	41
1990–1994	22	0.94	220	490	11[d]	1.8	48
1995–1997	19	0.87	280	340	11[d]	1.7	38
1998–2002	20	1.8	402	817	0.78	1.7[d]	59
Other (liquid)							
1970–1974	0.2[d]	2	5.5	0.6	0.2[d]	0.2[d]	2.1
1975–1979	0.18	0.29	4.8	0.47	0.18[d]	0.18[d]	0.7
1980–1984	0.13	0.12	4.5	0.026	0.13[d]	0.13[d]	0.38
1985–1989	0.056	0.036	1.2	0.03	0.045[d]	0.004	0.095
1990–1994	0.019	0.043	0.51	0.13	0.005	0.049	0.047
1995–1997	0.008	0.011	0.7	0.044	0.006	0.023	0.04
1998–2002	0.011	0.008	0.7[d]	0.260	0.002	0.023[d]	0.03

[a] Includes all PWRs and WWERs.
[b] Includes GCRs and AGRs.
[c] Weighted by the fraction of energy generated by the reactor types.
[d] Estimated values.

Table 18. Estimated average annual collective doses due to effluents from nuclear power plants for the period 1998–2002

Nuclides	*Quantity*	*PWR*[a]	*BWR*	*GCR*[b]	*HWR*	*LWGR*	*FBR*
Atmospheric releases							
Noble gases	Total release (PBq)	2.0×10^{0}	2.92×10^{0}	148×10^{-1}	1.0×10^{0}	2.5×10^{1}	1.4×10^{-2}
	Collective dose (man Sv)	2.2×10^{-1}	1.25×10^{0}	1.3×10^{-1}	1.1×10^{-1}	2.8×10^{0}	1.6×10^{-3}
Tritium	Total release (PBq)	3.9×10^{-1}	1.1×10^{-1}	1.7×10^{-2}	1.1×10^{1}	2.0×10^{-1}	2.0×10^{-2}
	Collective dose (man Sv)	8.2×10^{-1}	2.2×10^{-1}	3.6×10^{-2}	2.3×10^{1}	4.3×10^{-1}	4.1×10^{-2}
^{131}I	Total release (PBq)	5.6×10^{-5}	2.1×10^{-5}	3.6×10^{-7}	1.3×10^{-7}	7.9×10^{-5}	8.0×10^{-8}
	Collective dose (man Sv)	2.5×10^{-4}	1.8×10^{-4}	1.6×10^{-6}	5.7×10^{-6}	3.5×10^{-4}	3.6×10^{-7}
Particulates	Total release (PBq)	5.6×10^{-6}	3.3×10^{-3}	1.0×10^{-6}	3.8×10^{-7}	2.1×10^{-5}	4.0×10^{-8}
	Collective dose (man Sv)	4.8×10^{-3}	2.8×10^{0}	8.9×10^{-4}	3.3×10^{-4}	1.9×10^{-2}	3.5×10^{-5}
^{14}C	Total release (PBq)	4.1×10^{-2}	3.5×10^{-2}	7.0×10^{-3}	1.5×10^{-2}	1.0×10^{-2}	4.8×10^{-5}
	Collective dose (man Sv)	1.0×10^{1}	9.5×10^{0}	1.8×10^{0}	4.1×10^{0}	2.8×10^{0}	1.3×10^{-2}
Liquid releases							
Tritium	Total release (PBq)	3.7×10^{0}	1.2×10^{-1}	2.1×10^{0}	1.0×10^{1}	6.2×10^{-3}	6.8×10^{-4}
	Collective dose (man Sv)	2.4×10^{0}	7.8×10^{-2}	1.3×10^{0}	6.7×10^{0}	4.0×10^{-2}	4.4×10^{-4}
Others	Total release (PBq)	2.0×10^{-3}	5.3×10^{-4}	3.6×10^{-6}	3.3×10^{-3}	9.2×10^{-6}	9.2×10^{-6}
	Collective dose (man Sv)	6.7×10^{-1}	1.8×10^{-1}	1.2×10^{-3}	1.1×10^{0}	5.2×10^{-3}	3.0×10^{-3}

Summary[c]	
Total collective dose (man Sv)	75
Total normalized collective dose due to airborne effluents (man Sv/(GW a))	0.22
Total normalized collective dose due to liquid effluents (man Sv/(GW a))	0.05
Total normalized collective dose due to releases from nuclear power plants (man Sv/(GW a))	0.27

[a] Includes all PWRs and WWERs.
[b] Includes GCRs and AGRs.
[c] Weighted by the fraction of energy generated by the reactor types.

Table 19. Releases from reactors no longer in commercial operation

Reactor	*Shut down*	*Atmospheric releases in 2002 (GBq)*				*Liquid releases in 2002 (GBq)*	
		Noble gases	*Tritium*	*Iodine-131*	*Particulates*	*Tritium*	*Other nuclides*
BWR							
Big Rock Point-1	1997	0	9.5	0	0.001 6	0.15	0.12
Lacrosse-1	1987	0	1.1	0	0.000 5	3.1	0.60
Humboldt Bay	1976	0	0	0	0	0.15	0.008 5
Millstone-1	1998	0	33	0	0.000 5	0	0
Browns Ferry-1	1985	35 855	1 463	3.4	0.075	0	0
Dresden-1	1978	2 184	1 346	0.047	0.22	1 253	0.34
PWR							
Haddam Neck-1	1996	0	57	0	0.001 7	79	0.67
Maine Yankee-1	1977	0	47	0	0.001 8	7.2	0.097
Rancho Seco-1	1989	0	52	0	0.000 4	427	0.050
San Onofre-1	1992	0	53	0	0.000 07	214	0.42
Three Mile Island-2	1979	0	34	0	0	0.020	0.000 4
Trojan-1	1992	852	278	0	0	3	0.084
Yankee Rowe-1	1991	0	0	0	0	0	0
Zion-1	1998	0	0	0	0.006 6	0	0.000 4
Zion-2	1998	0	0	0	0.006 6	0	0.000 4
Indian Point-1	1974	31 997	16 262	0.020	1.6	19 703	10

Table 20. Collective doses due to fuel reprocessing

Airborne effluents						
Quantity	*^{3}H*	*^{14}C*	*^{85}Kr*	*^{129}I*	*^{131}I*	*^{137}Cs*
Total releases for the five-year period 1998–2002 (TBq)	2 001	44.16	2 160 300	0.14	0	0.003 2
Collective dose conversion factor (man Sv/TBq)	0.002 1	0.27	0.000 007 4	44	0.3	7.4
1998–2002 collective dose (man Sv)	4.20	11.9	16.0	6.17	0	0.024
Collective dose from all nuclides (man Sv)	38.31					
Average annual collective dose (man Sv)	7.66					
Normalized annual collective effective dose (man Sv/(GW a))	0.028					
Liquid effluents						
Quantity	*^{3}H*	*^{14}C*	*^{90}Sr*	*^{106}Ru*	*^{129}I*	*^{137}Cs*
Total release for the five-year period 1998–2002 (TBq)	84 473	105.5	133.6	131.9	12.18	39.44
Collective dose conversion factor (man Sv/TBq)	0.000 001 4	1	0.004 7	0.003 3	0.099	0.098
1998–2002 collective dose (man Sv)	0.118	105.5	0.63	0.44	1.21	3.87
Collective dose from all nuclides (man Sv)	111.8					
Average annual collective dose (man Sv)	22.35					
Normalized annual collective effective dose (man Sv/(GW a))	0.081 4					

Table 21. Spent fuel and arisings of low- and intermediate-level radioactive waste from nuclear power plants

Type	*Country*	*Reference plant*	*Spent fuel*[a]	*Low- and intermediate-level radioactive waste*	
			t/MW(e)	*m^3/MW(e)*	*Bq/MW(e)*
BWR	Spain Switzerland	Cofrentes, S.M.Garoña Leibstadt, Muehleberg	0.02	0.10	1.32×10^{10}
PHWR	Argentina Canada Korea, Rep.	Atucha Gentily-2, Point Lepreau Wolsong	0.18	0.07	1.02×10^{10}
PWR	Switzerland Korea, Rep. Spain	Beznau, Goesgen Kori, Ulchin, Yongwang Almaraz, Vandellós	0.02	0.04	5.17×10^{9}
WWER	Hungary	Paks	0.04	0.26	n.a.[b]

[a] Tonnes of heavy metal.
[b] Not available.

Table 22. Normalized collective effective doses (man Sv/(GW a)) to local and regional population groups due to radionuclides released in effluents of the nuclear fuel cycle

Source	*1970–1979*	*1980–1984*	*1985–1989*	*1990–1994*	*1995–1997*	*1998–2002*
Mining	0.19	0.19	0.19	0.19	0.19	0.19
Milling	0.008	0.008	0.008	0.008	0.008	0.008
Mine and mill tailings (releases over five years)	0.04	0.04	0.04	0.04	0.04	0.04
Fuel fabrication	0.003	0.003	0.003	0.003	0.003	0.003
Reactor operation						
Airborne effluents	2.8	0.7	0.4	0.4	0.4	0.22
Liquid effluents	0.4	0.2	0.06	0.05	0.04	0.05
Reprocessing						
Airborne effluents	0.3	0.1	0.06	0.03	0.04	0.028
Liquid effluents	8.2	1.8	0.11	0.10	0.09	0.081
Transportation	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
Total (rounded)	12	3.1	0.97	0.92	0.91	0.72

Table 23. Annual collective doses (man Sv) due to transport for three types of spent fuel management in Germany [B7]

Population group	*Comments*	*Nuclear reprocessing centre*[a]	*Integrated back-end concept*[b]	*Alternative back-end concept*[c]
Railway personnel handling radioactive material in shunting yards	Average: 0.52 man Sv per transport	4	10.8	3.9
Train drivers	No structure shielding considered	0.026	0.068	0.026
Railway passengers	124 passengers per train	0.2	0.51	0.2
Inhabitants in the proximity of shunting yards		0.054	0.110	0.052
Total	All population groups	4.3	12	4.2

[a] Transfer directly to nuclear reprocessing centres.
[b] Transfer using separate sites for interim storage of spent fuel, reprocessing and waste disposal.
[c] Direct disposal of spent fuel at the repository with no reprocessing.

Table 24. Number of packages and total activity of Suez Canal shipments from 1986 to 1992 [S1]

Material	*Package type*[a]	*Number of packages*	*Cumulative transport index*[b]	*Total activity (Bq)*
^{60}Co	B	36	122.4	5.06×10^{16}
^{137}Cs	A	30	59.1	5.68×10^{14}
UF_6	B	920	1 265.5	9.70×10^{13}
U_3O_8	A	1 852	9 651.4	5.85×10^{14}
UO_2	B	145	397.6	2.32×10^{13}
^{252}Cf	A	1	0.5	8.89×10^{9}
^{85}Kr	A	17	13.0	1.85×10^{13}
^{3}H	A	19	27.0	1.02×10^{14}

[a] Packages type refers to those described in reference [I33].
[b] The cumulative transport index refers to the sum of the transport index for all cargoes in the period 1986–1992.

Table 25. Number of packages containing radioactive material carried by aircraft in the United Kingdom in 2001 [W3]

Situation	*Short-haul*[a]				*Long-haul*[b]		*Total*
	Passenger		*Cargo*		*Passenger*	*Cargo*	
	Unit[c]	*Loose*[d]	*Unit*[c]	*Loose*[d]	*Unit*[c]	*Unit*[c]	
Into United Kingdom	245	981	4 111	4	2 920	1 383	9 644
From United Kingdom	2 533	3 104	14 540	2 746	13 197	26 015	62 135
Within United Kingdom	0	379	0	39	—	—	418
In transit	0	310	600	595	23	23	1 551
Number of consignments	25	1 042	2 530	337	2 840	90	6 864

[a] Short-haul: flights that take up to 4 h.
[b] Long-haul: flights that take over 4 h.
[c] Wide-body aircraft loaded with unit load devices (UDLs) to carry cargo.
[d] Narrow-bodied aircraft unable to take UDLs; cargo is loaded loose in the aircraft.

Table 26. Collective doses due to transport of radioactive material by air in the United Kingdom in 2001 [W3]

Exposed group	*Subgroup*	*Type of flight*	*Collective dose (man Sv/a)*
Handlers	—	All	0.1
Aircrew	Cabin crew	Short-haul passengers	0.13
		Long-haul passengers	3.8
	Flight crew	Short-haul passengers	0.002 5
		Short-haul cargo	0.024
		Long-haul passengers	0.13
		Long-haul cargo	0.56
Passengers	—	Short-haul passengers	0.43
	—	Long-haul passengers	2.8

Table 27. Estimated collective and individual doses to the public due to the normal transport of radioactive and nuclear material [I5, W8]

Country	*Period*	*Product*	*Mode of transport*	*Collective dose (man Sv/a)*	*Individual dose (mSv/a)*
Former GDR	1975–1984	Spent fuel	Road	0.15	0.01
Italy	1981	Fuel elements, PWR	Road	0.01	
United Kingdom	1981	Spent fuel	Road and rail	0.001	0.002
India	1982	Radioactive materials for medicine and industry	Road and air	0.1	*b*
Italy	1982	Medical use	Road	0.006	
United Kingdom	1982	All	Mainly road	0.004	0.04
Germany, Fed. Rep.	1983	Fresh and spent fuel, UF_6, ores, wastes	Rail	0.019	
Austria	1984	^{192}Ir, ^{99}Mo, ^{60}Co, ^{123}I, ^{131}I, ^{133}Xe	Air, road, rail	0.23	
Finland	1982–1985	Spent fuel	Road and rail	$(0.6–1.4) \times 10^{-3}$	
Turkey	1984	^{192}Ir, ^{60}Co, ^{131}I, ^{99m}Tc, ^{137}Cs, ^{241}Am	Road and air	0.429	
United States	1985	All from fuel cycle	All	19	0.02
		All	All	100	0.02
United Kingdom	2001	Medical and industrial sources	Air	3.23[a]	
United Kingdom	2003	Medical and industrial sources	Road	0.24	
United Kingdom	2003	Spent fuel	Road and rail	0.003	

[a] Doses to the public. Total annual collective dose, including passengers, crew and other workers, is 8 man Sv.
[b] Dose rate to the public: 1–55 μGy/h.

Table 28. Maximum annual doses (μSv) to members of the public due to the transport of various fuel cycle materials and by various modes [W14]

Material	*Road*	*Rail*	*Sea*
Non-irradiated material	<4	<1	<20
Spent fuel	<4	<6	<1
Waste (low- and intermediate-level)	<4	<4	
High-level waste		20	<1
MOX/plutonium			<1

Table 29. Doses to the public from consumer products and miscellaneous items
Conservative estimates [W6]

Item	*Estimated annual individual effective dose (μSv)*
Radioluminous wristwatch containing ^{147}Pm	0.3
Radioluminous wristwatch containing ^{3}H	10
Smoke alarms	0.07
Uranium glazed wall tiles	<1
Geological specimens	100
Photographic lenses[a]	200–300
^{210}Po in tobacco [C23, N9]	10

[a] No longer in use.

Table 30. Annual doses from by-products and radioactive materials in the United States [U35]

Effective dose (mSv)	*By-product*
<0.01	Automobile lock illuminators Precision balances Automobile shift quadrants Marine compasses and navigational instruments Thermostat dials and pointers Self-luminous products
0.01–<0.1	Timepieces, hands and dials Electron tubes Gas and aerosol detectors
0.1–<1.0	Ionizing radiation measurement instruments Spark gap irradiators
Effective dose (mSv)	*Source material*
<0.01	Vacuum tubes Electric lamps for illuminating purposes Germicidal lamps, sunlamps and lamps for outdoor or industrial lighting Personnel neutron dosimeters Piezoelectric ceramic Photographic film, negatives and prints Uranium in fire detection units
0.01–<0.1	Glassware Uranium shielding in shipping containers
0.1–<1.0	Glazed ceramic tableware Finished tungsten–thorium or magnesium–thorium alloy products or parts Uranium in counterweights Thorium in finished optical lenses Aircraft engine parts containing nickel–thorium alloy
1.0–<10	Unrefined and unprocessed ore Incandescent gas mantles Welding rods
≥10	Chemical mixtures, compounds, solutions or alloys Rare earth metals and compounds, mixtures and products

Table 31. Summary of annual per caput doses due to peaceful uses of atomic energy (*μ*Sv)

Local component		
Nuclear fuel cycle and energy generation	Mining and milling	25
	Fuel fabrication	0.2
	Reactor operation	0.1
	Reprocessing	2
Other uses	Transport of radioactive waste	<0.1
	By-products	0.2
Regional component		
Nuclear fuel cycle and energy generation	Fuel fabrication	<0.01
	Reactor operation	<0.01
	Reprocessing	0.02
Solid waste disposal and global component		
Nuclear fuel cycle and energy generation	Globally dispersed radionuclides	0.2
Other uses	Disposal of radioactive waste	<0.01

Table 32. Atmospheric nuclear tests at each test site [adapted from reference U3]

Test site	*Number of tests*	*Yield (Mt)*			*Partitioned fission yield (Mt)*		
		Fission	*Fusion*	*Total*	*Local and regional*	*Troposphere*	*Stratosphere*
China							
Lop Nor	22	12.2	8.5	20.72	0.15	0.66	11.4
France							
Algeria	4	0.073	0	0.073	0.036	0.035	0.001
Fangataufa	4	1.97	1.77	3.74	0.06	0.13	1.78
Mururoa	37	4.13	2.25	6.38	0.13	0.41	3.59
Total	45	6.17	4.02	10.19	0.23	0.58	5.37
United Kingdom							
Monte Bello Island	3	0.1	0	0.1	0.05	0.049	0.000 7
Emu	2	0.018	0	0.018	0.009	0.009	0
Maralinga	7	0.062	0	0.062	0.023	0.038	0
Malden Island	3	0.69	0.53	1.22	0	0.56	0.13
Christmas Island	6	3.35	3.3	6.65	0	1.09	2.26
Total	21	4.22	3.83	8.05	0.08	1.75	2.39
United States							
New Mexico	1	0.021	0	0.021	0.011	0.01	0
Nevada	86	1.05	0	1.05	0.28	0.77	0.004
Bikini	23	42.2	34.6	76.8	20.3	1.07	20.8
Enewetak	42	15.5	16.1	31.7	7.63	2.02	5.85
Pacific	4	0.102	0	0.102	0.025	0.027	0.05
Atlantic	3	0.004 5	0	0.004 5	0	0	0.005
Johnston Island	12	10.5	10.3	20.8	0	0.71	9.76
Christmas Island	24	12.1	11.2	23.3	0	3.62	8.45
Total	195	81.5	72.2	153.8	28.2	8.23	44.9

Test site	*Number of tests*	*Yield (Mt)*			*Partitioned fission yield (Mt)*		
		Fission	*Fusion*	*Total*	*Local and regional*	*Troposphere*	*Stratosphere*
Former Soviet Union							
Semipalatinsk	116	3.74	2.85	6.59	0.097	1.23	2.41
Novaya Zemlya	91	80.8	158.8	239.6	0.036	2.93	77.8
Totsk, Aralsk	2	0.04	0	0.04	0.000 15	0.037	0.003
Kapustin Yar	10	0.68	0.3	0.98	0	0.078	0.61
Total	219	85.3	162	247.2	0.13	4.28	80.8
All countries							
Total	502	189	251	440	29	15	145

Table 33. Number and total yield of weapons tests and other events by country [B16, U3]

Type	*United States*	*Former Soviet Union*	*United Kingdom*	*France*	*China*	*India*	*Pakistan*	*Democratic People's Republic of Korea*	*Total*
Atmospheric nuclear tests									
Airburst	13	8	9	0	0	0	0	0	30
Air drop	52	174	1	3	16	0	0	0	246
Balloon	24	0	1	34	0	0	0	0	59
Tower/surface	66	34	10	4	6	0	0	0	120
Barge	35	0	0	4	0	0	0	0	39
Underwater	5	3	0	0	0	0	0	0	8
Total	195	219	21	45	22	0	0	0	502
Fission (Mt)	82	85	4	6	12	0	0	0	189
Fusion (Mt)	72	162	4	4	9	0	0	0	251
Underground nuclear tests									
Number of tests	908	750	24	160	22	6	6	1	1 877
Yield (Mt)	46	38	2	3	1				90
Total atmospheric and underground tests									
Number of tests	1 103	969	45	205	44	6	6	1	2 379
Yield (Mt)	200	285	10	13	22				530
Other events with nuclear weapons									
Safety trials	22	0	12	5	0	0	0	0	39
Operational	2	0	0	0	0	0	0	0	2

Table 34. Radionuclides produced and globally dispersed in atmospheric nuclear tests [U3]

Radionuclide	*Half-life*	*Global release (PBq)*
^{3}H	12.33 a	186 000
^{14}C	5 730 a	213
^{54}Mn	312.3 d	3 980
^{55}Fe	2.73 a	1 530
^{89}Sr	50.53 d	117 000
^{90}Sr	28.78 a	622
^{91}Y	58.51 d	120 000
^{95}Zr	64.02 d	148 000
^{103}Ru	39.26 d	247 000
^{106}Ru	373.6 d	12 200
^{125}Sb	2.76 a	741
^{131}I	8.02 d	675 000
^{140}Ba	12.75 d	759 000
^{141}Ce	32.5 d	263 000
^{144}Ce	284.9 d	30 700
^{137}Cs	30.07 a	948
^{239}Pu	24 110 a	6.52
^{240}Pu	6 563 a	4.35
^{241}Pu	14.35 a	142

Table 35. Latitudinal distribution of radionuclides from atmospheric nuclear tests based on ^{90}Sr measurements [U3]

Latitude band (°)	*Population distribution (%)*	*Integrated deposition of ^{90}Sr (PBq)*	*Deposition in band (%)*	*Deposition density per unit deposition ((Bq/m^2)/PBq)*	*Latitudinal value relative to hemispheric value*
Northern hemisphere					
80–90	0	1	0.2	0.56	0.12
70–80	0	7.9	1.7	1.48	0.32
60–70	0.4	32.9	7.1	3.78	0.81
50–60	13.7	73.9	16.1	6.27	1.35
40–50	15.5	101.6	22.1	7.01	1.51
30–40	20.4	85.3	18.5	5.09	1.09
20–30	32.7	71.2	15.5	3.85	0.83
10–20	11	50.9	11.1	2.58	0.56
0–10	6.3	35.7	7.8	1.76	0.38
Southern hemisphere					
80–90	0	0.3	0.2	0.53	0.14
70–80	0	2.5	1.7	1.5	0.4
60–70	0	6.7	4.6	2.46	0.66
50–60	0.5	12.1	8.4	3.28	0.88
40–50	0.9	28.1	19.5	6.19	1.65
30–40	13	27.6	19.1	5.26	1.4
20–30	14.9	28.1	19.5	4.85	1.29
10–20	16.7	17.8	12.3	2.89	0.77
0–10	54	21	14.6	3.3	0.88

Table 36. Estimated average effective doses (μSv) due to global fallout received by the world population [B46, U3, U6]

Radionuclide	*Received before 2000*				*To be received 2000–2100*	*To be received beyond 2100*
	External irradiation	*Inhalation*	*Ingestion*	*All pathways*	*All pathways*	*All pathways*
^{3}H	—	—	24	24	0.1	
^{14}C	—	—	144	144	120	2 230
^{54}Mn	19	0.1		19	—	
^{55}Fe	—	0.01	6.6	6.6	—	
^{89}Sr	—	2.6	1.9	4.5	—	
^{90}Sr	—	9.2	97	106	8.6	0.02
^{91}Y	—	4.1	—	4.1	—	
^{95}Zr	81	2.9	—	84	—	
^{103}Ru	12	0.9	—	13	—	
^{106}Ru	25	35	—	60	—	
^{125}Sb	12	0.1	—	12	0.003	
^{131}I	1.6	2.6	64	68	—	
^{140}Ba	27	0.4	0.5	28	—	
^{141}Ce	1.1	0.8	—	1.9	—	
^{144}Ce	7.9	52	—	60	—	
^{137}Cs	166	0.3	154	320	124[a]	13
^{239}Pu	—	20	—	20	—	
^{240}Pu	—	13	—	13	—	
^{241}Pu	—	5	—	5	—	
Total	353	149	492	994	253	2 243

[a] 114 μSv from external irradiation and 10 μSv from internal irradiation.

Table 37. Estimated effective doses for several regions of Maralinga and Emu [H7]

Zone	*Annual effective dose (mSv)*	*Principal pathway*	*Principal nuclide*
Taranaki North Plume, ^{241}Am A contour 10-year-old child	5	Inhalation	^{239}Pu
Taranaki Northwest, ^{241}Am A contour 10-year-old child	4	Inhalation	^{239}Pu
Kuli ^{238}U D contour 10-year-old child	23	Inhalation; external gamma	$^{234/238}$U
Kuli ^{238}U A contour 10-year-old child	3	Inhalation; external gamma	$^{234/238}$U
Northeast One Tree: 2 kBq/m^2 of ^{137}Cs 3-month-old infant	2	Soil ingestion; inhalation	^{239}Pu
TM100, ^{241}Am A contour 10-year-old child	5	Inhalation	^{239}Pu
Emu—Totem II, ^{241}Am A contour 10-year-old child	9	Inhalation	^{239}Pu

Zone	*Annual effective dose (mSv)*	*Principal pathway*	*Principal nuclide*
Emu—Totem I, ^{137}Cs A contour 10-year-old child	0.5	Inhalation; ingestion	^{239}Pu
Inner Taranaki 10-year-old child	470	Inhalation	^{239}Pu
Emu—centre of Totem II 10-year-old child	31	Inhalation	^{239}Pu

Table 38. Median (and mean) activities[a] of ^{137}Cs, ^{90}Sr, $^{239+240}$Pu and ^{241}Am per unit dry weight of soil on Bikini Island (Bq/g) [I9]

Soil depth (cm)	*^{137}Cs*	*^{90}Sr*	*$^{239+240}$Pu*	*^{241}Am*
Interior of island				
0–5	2.3 (3.0)	1.7 (2.1)	0.32 (0.42)	0.26 (0.30)
0–40	0.70 (0.91)	1.1 (1.5)	0.17 (0.21)	0.11 (0.14)
Village area				
0–5	1.2 (2.0)	1.0 (2.0)	0.20 (0.40)	0.11 (0.22)
0–40	0.67 (1.1)	1.6 (1.5)	0.24 (0.29)	0.13 (0.17)

[a] Decay corrected to 1999. The numbers in parentheses are the arithmetic means.

Table 39. Radionuclide and pathway contributions to hypothetical doses on Bikini Island assuming a local diet [I9]

Exposure pathway		*Annual dose (mSv)*
External gamma		0.4
Ingestion	^{137}Cs	14.6
	^{90}Sr	0.15
	$^{239+240}$Pu	0.001 9
	^{241}Am	0.001
Inhalation	$^{239+240}$Pu	0.000 74
	^{241}Am	0.000 49
Total (rounded)		15

Table 40. Absorbed dose rates in air in settlements outside and inside the Semipalatinsk nuclear test site [I10]

Location	*Dose rate at 1 m above ground (μGy/h)*
Outside the nuclear test site	
Entire perimeter (over 500 measurements)	0.06–0.17
Dolok	0.07
Sarzhal and surrounding pasture	0.08–0.09
Kainar	0.08–0.11
Akzhar and surrounding pasture	0.08
Dolon	0.09
Other settlements	0.07–0.14

Location	*Dose rate at 1 m above ground (μGy/h)*
Inside the nuclear test site	
Lake Balapan	0.1–33
Ground Zero	
1 km from centre	0.1
Within 1 km	0.1–17
South-eastern plume	0.09
Polygon farm	0.1
Beriozka State Farm	0.2
Sary-Uzen	0.5
Lake Tel'kem-2	0.2–1.0

Table 41. Estimated annual effective doses to persons living around the Semipalatinsk test site, to visitors to Lake Balapan and Ground Zero, and to potential future permanent inhabitants

Pathway	*Annual dose (mSv)*			
	Outside test area		*Inside test area*	
	Dolon	*Other settlements*	*Frequent visitors*	*Future permanent inhabitants*
External gamma	0.01	0.01	10	90
Inhalation				
^{238}Pu	0.007		0.05	1.2
$^{239+240}$Pu	0.04	0.01	0.2	3.5
^{241}Am	0.004		0.02	0.4
Ingestion				
^{137}Cs	0.03	0.03	3	30
^{90}Sr	0.02	0.02	0.06	10
^{238}Pu	0.004		0.07	0.6
$^{239+240}$Pu	0.02	0.001	0.2	2
^{241}Am	0.002		0.02	0.2
Total (rounded)	0.14	0.06	14	140

Table 42. Summary of residual radionuclide inventory on the Nevada Test Site as of January 1996 [U25]

Source of radioactivity	*Type of area*	*Environmental media*	*Major known isotopes or wastes*	*Depth*	*Activity (Bq)*
Atmospheric and tower tests	Above-ground nuclear weapons proving area	Surficial soil and test structures	Am, Cs, Co, Pu, Eu, Sr	At land surface	$\sim 7.4 \times 10^{10}$
Safety trials	Above-ground experimental area	Surficial soil	Am, Cs, Co, Pu, Sr	$<$0.9 m	$\sim 1.3 \times 10^{12}$
Nuclear rocket development area	Nuclear rocket, motor, reactor and furnace testing area	Surficial soil	Cs, Sr	$<$3 m	$\sim 3.7 \times 10^{10}$
Shallow borehole tests	Underground nuclear testing area	Soils and alluvium	Am, Cs, Co, Eu, Pu, Sr	$<$61 m	$\sim 7.4 \times 10^{13}$
Shallow land disposal	Waste disposal landfill	Soils and alluvium	Dry packaged low-level and mixed wastes	$<$9 m	$\sim 1.85 \times 10^{15}$
Crater disposal	Test-induced subsidence crater with sidewalls, cover and drainage	Soils and alluvium	Bulk contaminated soil and equipment	$<$30 m	$\sim 4.6 \times 10^{13}$
Greater confinement disposal	Monitored underground waste disposal borehole	Soils and alluvium	Am, tritium	37 m	$\sim 3.4 \times 10^{17}$ ($\sim 300 \times m^3$)
Deep underground tests	Underground nuclear testing area	Soils, alluvium and consolidated rock	Tritium, fission and activation products	Typically less than 640 m but may be deeper	$> 1.1 \times 10^{19}$

Table 43. Properties of uranium isotopes ^{238}U, ^{235}U and ^{234}U and their relative abundance in natural and depleted uranium [I7]

Isotope	*Average energy per transformation (MeV/Bq)*			*Half-life*	*Natural uranium*			*Depleted uranium*		
					Specific activity	*Relative isotopic abundance (%)*		*Specific activity*	*Relative isotopic abundance (%)*	
	Alpha	*Beta*	*Gamma*	*(a)*	*(Bq/mg U)*	*By mass*	*By activity*	*(Bq/mg U)*	*By mass*	*By activity*
^{238}U	4.26	0.01	0.001	4.51×10^9	12.44	99.28	48.2	12.44	99.8	87.5
^{235}U	4.47	0.04	0.154	7.1×10^8	0.6	0.72	2.2	0.16	0.2	1.1
^{234}U	4.84	0.001 3	0.002	2.47×10^5	12.44	0.005 5	49.5	1.61	0.000 7	11.4

Table 44. Estimated amount of depleted uranium used in armed conflict

Conflict	*Total DU (t)*
Gulf War I (1991)	286
Bosnia and Herzegovina (1994–1995)	3
Kosovo (1999)	10
Serbia and Montenegro (1999)	0.7

Table 45. Lands contaminated with radionuclides at enterprises of Minatom of Russia
As of 1 January 2000 [L2]

Enterprise	*Area (km^2)*	*Area (km^2) with exposure rates of greater than 2 μGy/h*
Priargun Mining and Chemical Association	8.53	—
Mining and Metallurgical Plant (Lermontov)	1.34	1.03
Machine-building Plant (Elektrostal)	0.26	0.261
Novosibirsk Plant of Chemical Concentrates	0.15	0.14
Moscow Plant of Polymetals	0.016	0.001
Chepetsk Mechanical Plant (Glazov)	1.35	0.062
Zabaikalski Mining and Enrichment Combine	0.04	
Mayak Production	452.16	65.7
Mining and Chemical Complex (Zheleznogorsk)	4.7	0.203
Siberian Chemical Complex (Seversk)	10.39	4.191
Kirovo-Chepetsk Chemical Complex	0.7	
All-Russian Research Institute of Technical Physics (Snezhinsk)	0.13	0.01
Research Institute of Atomic Reactors (Dimitrovgrad)	0.39	0.081
Institute of Physics and Power Engineering (Obninsk)		0.001
Total	480.32	71.68

Table 46. Number of particles retrieved and their average activity close to the Dounreay site as of May 2007 [D5]

Particle location	*Number of particles found*	*Average particle activity (Bq)*
Marine sediment	930	1.4×10^6
Dounreay offshore	248	5.5×10^6
Sandside Beach	94	7.3×10^4
Dunnet Beach	1	8.9×10^3
Murkle Beach	1	1.3×10^4
Dounreay site (estimate)	86	n.a.[a]

[a] Not available.

Table 47. Maximum total annual individual doses estimated for selected population groups close to the Kara Sea [I11]

Scenarios	*Annual doses (μSv)*	
	Seafood consumers – Groups (a) and (c)	*Military personnel – Group (b)*
Best estimate scenario	<0.1	700
Plausible worst scenario	<1	4 000
Climate change scenario	0.3	3 000

Groups:
(a) Living in Ob and Yenisei estuaries and on Taimyr and Yamal peninsulas; habits typical of subsistence fishing communities in Arctic.
(b) Hypothetical group of military personnel patrolling, for 100 hours in a year, foreshores of fjords containing dumped radioactive material.
(c) Seafood consumers representative of northern Russian population situated on Kola Peninsula.

Table 48. Practices for which UNSCEAR evaluates occupational exposure

Category of practice	*Practice*
Exposure to natural sources of radiation	Civilian aviation Coal mining Other mineral mining Oil and natural gas industries Workplace exposure to radon other than in mines
Nuclear fuel cycle	Uranium mining Uranium milling Uranium enrichment and conversion Fuel fabrication Reactor operation Decommissioning Fuel reprocessing Research in the nuclear fuel cycle Waste management
Medical uses	Diagnostic radiology Dental radiology Nuclear medicine Radiotherapy All other medical uses
Industrial uses	Industrial irradiation Industrial radiography Luminizing Radioisotope production Well logging Accelerator operation All other industrial uses
Miscellaneous	Educational establishments Veterinary medicine Other occupations
Military activities	All military activities

Table 49. Occupational exposure of aircrew

Data from the UNSCEAR Global Survey of Occupational Radiation Exposures and the literature [S38]

Country	*Number of workers*	*Collective dose (man Sv)*	*Average effective dose (mSv)*	*Maximum effective dose (mSv)*
Canada	100	0.6	1.36	
Czech Republic	1 195	1.5	1.28	3.5
Denmark	3 990	6.8	1.7	—
Finland	2 520	4.2	1.7	—
Germany	31 000	60.0	2.0	6.5
Lithuania	160	0.2	1.2	
Netherlands	12 500	17.0	1.3	<6
United Kingdom	40 000	80.0	2.0	—
United States	150 000[a]		0.2–5.0[b]	

[a] Data from reference [U27].
[b] Data from references [W2, W16].

Table 50. Estimated effective doses for specific flight routes leaving Frankfurt, Germany

Destination	*Range of the dose[a] (μSv)*
Gran Canaria	10–18
Johannesburg	18–30
New York	32–75
Rio de Janeiro	17–28
Rome	3–6
San Francisco	45–110
Singapore	28–50

[a] A range of values is given because of differences in flying altitude and variations in the intensity of the cosmic ray flux due to varying solar activity.

Table 51. Dose equivalent rate and mission dose equivalent in crewed space missions [R7, R8]

Mission	*Inclination (grad)*	*Altitude (km)*	*Mission duration (h)*	*Dose equivalent rate (mSv/d)*	*Mission dose equivalent (mSv)*
SL1	57	250	247.5	0.46	4.7
D-1	57	324	168	0.48	3.3
IML-1	57	348	194	0.38	3.0
MIR92	51.5	400	190	0.64	5.1
D-2	28.5	296	240	0.19	1.9
IM-L2	28.5	296	353	0.26	3.8
Euromir '94	51.5	400	756	~0.86	~27

Table 52. Annual doses to underground coal miners in China [C12]

Type of coal mine	*Average annual effective dose (mSv)*	*Collective dose (man Sv)*
Large-sized	0.28	280
Medium-sized	0.55	550
Small-sized	3.3	13 200
Bone-coal	10.9	545
Average	2.4	14 600

Table 53. Occupational exposure in underground gold mines in South Africa [W17]

Year	*Average annual dose (mSv)*	*Number of workers*	*Number of workers receiving doses of >20 mSv*
1997	6.3	258 080	12 904
1998	4.9	232 500	2 325
1999	5.4	175 333	5 260
2000	7	123 333	3 700

Table 54. Estimated external doses for workers in Abu-Tartor phosphate mine tunnels
Estimates based on individual and workplace monitoring using TLDs [K11]

Type of worker	*Mean*	*SE*[a]	*SD*[b]	*Minimum*	*Maximum*	*Number*[c]
Effective dose rate estimated using individual monitoring (mSv/a)						
Mine workers	15.55	2.73	12.20	6.78	53.52	20
Mine maintenance workers	10.25	0.97	3.64	5.90	18.23	14
Ore crushing and transport workers	11.34	1.03	1.78	9.83	13.31	3
Beneficiation factory workers	10.95	0.35	0.79	10.09	12.11	5
Ore drying and storage workers	10.21	0.15	0.26	9.97	10.49	3
Average	11.66	—	—	—	—	—
Effective dose rate estimated using workplace monitoring (mSv/a)						
Mine	8.51	0.60	3.36	2.19	17.09	31
Ore crushing	10.06	0.31	0.70	8.94	10.81	5
Processing facility	8.35	0.52	1.08	6.82	9.07	4
Average	8.97	—	—	—	—	—

[a] Standard error of the mean.
[b] Standard deviation.
[c] Number of measurements.

Table 55. Doses received by workers in zircon milling plants [I41]

Location	*Annual effective dose (mSv)*		
	Gamma radiation	*Dust inhalation*[a]	*Total*
Australia			
— New autogenous mill, dust extraction, enclosed bagging, good industrial hygiene	0.4	0.27	0.67
— Old roller mill, no special dust extraction during bagging	0.3	0.73	1.03
— Old ball mill, no special dust extraction	0.1	0.56	0.66
— Old ball mill, semi-automatic bagging, no special dust extraction	0.4	0.56	0.96
Netherlands			0.8
South Africa			
— Mill operators (mill areas)	0.102	0.163	0.265
— Mill operators and maintenance personnel (warehouse)	0.238	0.046	0.284
— Maintenance personnel (mill areas)	0.067	0.042	0.109
— General workers (mill areas)	0.096	0.06	0.156
— General workers (warehouse)	0.210	0.04	0.250
South Africa[c]			
— Mill attendant	0.275	0.165	0.44
— Shift supervisor	0.18	0.094	0.274
— Cleaner	0.2	0.134	0.33
South Africa			
— Wet mill operator	0.16	0	0.16
United Kingdom		0.5	
United States: bagger operator (respiratory protection mandatory)			
— Without respiratory protection[b]	0.2	1.9	2.1
— With respiratory protection			<1

[a] Except where otherwise stated, values are based on the assumption that no respiratory protection was used.
[b] Doses calculated from values of gamma exposure, airborne dust activity concentration and occupancy period using the inhalation dose coefficients for an AMAD of 5 μm.
[c] Maximum values measured after implementation of the following dose reduction measures: reduction of dust generation through revised engineering practices, reduction of stockpile quantities and thus of gamma exposures, and reduction of surface contamination by continuous cleaning practices [I41].

Table 56. Occupational exposure in Germany due to radon inhalation in workplaces other than mines
Data from the UNSCEAR Global Survey of Occupational Radiation Exposures

Workplace	*Period*	*Monitored workers (10^3)*	*Measurably exposed workers (10^3)*	*Annual collective effective dose (man Sv)*	*Average annual effective dose (mSv)*	
					Monitored workers	*Measurably exposed workers*
Spas	1995–1999	0.002	0.002	0.01	4.77	4.77
	2000–2002	0.004	0.002	0.01	4.09	4.47
Waterworks	1995–1999	0.128	0.075	0.24	1.85	3.12
	2000–2002	0.081	0.047	0.11	1.39	2.50
Tourist caves and visitor mines	1995–1999	0.135	0.101	0.31	2.26	3.01
	2000–2002	0.131	0.087	0.23	1.76	2.63

Table 57. Estimated worldwide levels of annual exposure due to natural sources of radiation for the period 1995–2002
Data from the UNSCEAR Global Survey of Occupational Radiation Exposures and the literature

Workplace	*Monitored workers (10^3)*	*Annual collective effective dose (man Sv)*	*Average annual effective dose (mSv)*
Coal mining	6 900	16 560	2.4
Other mining (excluding uranium mining)	4 600	13 800	3.0
Workplaces other than mines	1 250	6 000	4.8
Aircrew	300	900	3.0
Total	13 050	37 260	2.9

Table 58. Estimated worldwide levels of annual exposure in uranium mining
Data from the UNSCEAR Global Survey of Occupational Radiation Exposures

Period	*Annual amount of ore extracted (kt U)*	*Collective dose per unit mass (man Sv/kt)*	*Monitored workers (10^3)*	*Annual collective dose (man Sv)*	*Annual effective dose (mSv)*
1975–1979	52	26	240	1 300	5.5
1980–1984	64	23	310	1 600	5.1
1985–1989	59	20	260	1 100	4.4
1990–1994	39	8	69	310	4.5
1995–1999	34	2	22	85	3.9
2000–2002	34	1	12	22	1.9

Table 59. Exposure to workers from underground and above-ground uranium mining
Data from the UNSCEAR Global Survey of Occupational Radiation Exposures

Country/type of uranium mine	*Period*	*Monitored workers (10^3)*		*Annual collective effective dose (man Sv)*	*Average annual effective dose (mSv)*	
		Total	*Measurably exposed*		*Total*	*Measurably exposed*
Canada						
Above-ground	1995–1999	1.30	0.64	0.61	0.44	0.97
	2000–2002	1.06	0.50	0.48	0.45	0.99
Underground	1995–1999	1.03	0.77	3.05	3.13	4.13
	2000–2002	0.65	0.48	1.46	0.95	2.00
Germany						
Above-ground	1995–1999	0.73	0.73	0.96	1.32	1.32
	2000–2002	0.53	0.53	0.15	0.28	0.28
Underground[a]	1995–1999	1.04	0.90	2.10	2.01	2.46
	2000–2002	0.88	0.88	0.94	1.07	1.07

[a] Extracted only in connection with decommissioning of mining facilities.

Table 60. Contribution of internal and external exposure to the effective dose due to uranium mining
Data from the UNSCEAR Global Survey of Occupational Radiation Exposures

Type of mine	*Percentage contribution of internal and external exposure to the effective dose*					
	Dose less than 1 mSv			*Dose more than 1 mSv*		
	Radon progeny	*Ore dust*	*External exposure*	*Radon progeny*	*Ore dust*	*External exposure*
Canada						
Underground	82%	—	—	62%	—	—
Above-ground	74%	—	—	41%	—	—
Czech Republic						
Underground	45%	39%	16%	72%	20%	8%
Germany						
Underground	36%	32%	32%	37%	53%	10%
Above-ground	23%	34%	43%	51%	40%	9%

Table 61. Effective dose to workers in above-ground and underground uranium mines
Reports on Canadian occupational radiation exposure [H9, H10, H11, H12, H13, H14]

Year	*Personnel*			*Maintenance*			*Miner*		
	Number of workers	*Average effective dose (mSv)*	*Per cent radon progeny*	*Number of workers*	*Average effective dose (mSv)*	*Per cent radon progeny*	*Number of workers*	*Average effective dose (mSv)*	*Per cent radon progeny*
Above-ground uranium mines									
1995	50	0.59	80	211	1.31	77	154	1.24	59
1996	61	0.75	71	247	1.33	73	214	1.30	51
1997	102	0.32	62	202	0.55	66	244	0.94	23
1998	126	0.37	79	176	0.36	93	96	0.80	50
1999	177	0.35	62	219	0.40	73	74	0.83	11
2000	186	0.64	74	194	0.64	45	89	1.35	52
2001	208	0.58	68	189	0.57	51	47	2.15	55
Underground uranium mines									
1995	368	0.98	64	109	5.37	66	386	10.90	63
1996	387	0.82	60	101	3.85	62	469	9.62	58
1997	476	0.69	39	103	1.48	64	354	5.53	39
1998	346	0.55	75	139	0.93	87	362	1.97	78
1999	155	1.01	71	204	0.90	79	341	2.60	63
2000	111	0.88	53	194	0.71	70	284	2.57	40
2001	73	0.48	54	115	0.46	64	161	2.29	32

Table 62. Estimated worldwide levels of exposure due to uranium milling
Data from the UNSCEAR Global Survey of Occupational Radiation Exposures

Period	*Annual amount of ore refined (kt U)*	*Equivalent amount of energy (GW a)*	*Monitored workers (10^3)*	*Collective effective dose (man Sv)*	*Average annual effective dose (mSv)*
1975–1979	53	240	12	124	10.1
1980–1984	64	290	23	117	5.1
1985–1989	58	260	18	116	6.3
1990–1994	39	180	6	20	3.3
1995–1999	34	155	3	4	1.6
2000–2002	34	155	3	3	1.1

Table 63. Contribution of internal and external exposure to the effective dose due to uranium milling
Data from the UNSCEAR Global Survey of Occupational Radiation Exposures

Uranium milling	*Percentage contribution of internal and external exposure to the effective dose*					
	Dose less than 5 mSv			*Dose more than 5 mSv*		
	Radon progeny	*Ore dust*	*External exposure*	*Radon progeny*	*Ore dust*	*External exposure*
Canada	70			50		
Germany	35	35	30	19	72	9

Table 64. Estimated worldwide levels of exposure due to uranium enrichment
Data from the UNSCEAR Global Survey of Occupational Radiation Exposures

Period	*Monitored workers (10^3)*	*Collective effective dose (man Sv)*	*Average effective dose (mSv)*
1975–1979	11.0	5.30	0.46
1980–1984	4.3	0.78	0.18
1985–1989	5.0	0.43	0.08
1990–1994	12.6	1.28	0.10
1995–1999	17.2	1.34	0.08
2000–2002	18.2	1.70	0.09

Table 65. Estimated worldwide levels of exposure due to fuel fabrication
Data from the UNSCEAR Global Survey of Occupational Radiation Exposures

Period	*Monitored workers (10^3)*	*Annual collective effective dose (man Sv)*	*Average annual effective dose (mSv)*
1975–1979	20	36	1.8
1980–1984	21	21	1.0
1985–1989	28	22	0.8
1990–1994	21	22	1.0
1995–1999	22	30	1.4
2000–2002	20	31	1.6

Table 66. Summary of worldwide exposures due to reactor operations

Period	*PWR*	*BWR*	*HWR*	*GCR*	*LWGR*	*All*
Average number of monitored workers (10^3)						
1975–1979	63	59	7	13	5	147
1980–1984	140	102	14	25	10	291
1985–1989	230	139	18	31	13	431
1990–1994	310	160	20	30		530
1995–1999	265	144	18	21		448
2000–2002	283	113	23	18		437
Average annual effective dose to monitored workers (mSv)						
1975–1979	3.5	4.7	4.8	2.8	6.6	4.1
1980–1984	3.1	4.5	3.2	1.4	6.4	3.6
1985–1989	2.2	2.4	3.4	0.8	13.2	2.5
1990–1994	1.3	1.6	1.7	0.5		1.4
1995–1999	1.9	1.7	1.6	0.3		1.5
2000–2002	1.7	1.4	1.6	0.2		1.0
Average annual collective effective dose (man Sv)						
1975–1979	220	279	32	36	36	603
1980–1984	450	454	46	34	62	1 046
1985–1989	500	331	60	24	173	1 088
1990–1994	415	240	35	16	190	896
1995–1999	506	237	29	7		779
2000–2002	415	160	38	4		617
Normalized collective effective dose per unit electrical energy (man Sv/(GW a))						
1975–1979	8.1	18.3	11.0	6.6	8.2	10.9
1980–1984	8.0	18.0	8.0	5.8	8.3	10.4
1985–1989	4.3	7.9	6.2	3.2	16.7	5.7
1990–1994	2.8	4.8	3.0	2.0	20.3	3.9
1995–1999	3.0	3.8	2.4	0.7		2.5
2000–2002	2.2	2.4	2.9	2.6		2.5
Normalized collective effective dose per reactor (man Sv per reactor)						
1975–1979	2.8	5.5	2.6	0.9	3.0	3.1
1980–1984	3.3	7.0	2.4	0.8	3.8	3.7
1985–1989	2.3	4.0	2.3	0.5	8.7	2.8
1990–1994	1.7	2.7	1.1	0.4	9.4	2.1
1995–1999	2.0	2.6	1.2	0.2		1.5
2000–2002	1.6	1.8	1.0	0.2		1.1

Table 67. Annual occupational doses for reactor operation by job category
From ISOE and Canadian National Dose Registry

Country	*Refuelling*[a]			*Maintenance*[b]			*Inspection*[c]			*Servicing*[d]			*Other*		
	Annual collective effective dose			*Annual collective effective dose*			*Annual collective effective dose*			*Annual collective effective dose*			*Annual collective effective dose*		
	Average number of reactors over the period	*Total (man mSv)*	*Average per reactor (man mSv)*	*Average number of reactors over the period*	*Total (man mSv)*	*Average per reactor (man mSv)*	*Average number of reactors over the period*	*Total (man mSv)*	*Average per reactor (man mSv)*	*Average number of reactors over the period*	*Total (man mSv)*	*Average per reactor (man mSv)*	*Average number of reactors over the period*	*Total (man mSv)*	*Average per reactor (man mSv)*
1995–1999															
BWR															
Germany	4.4	284.5	64.7	5.8	1 851.7	319.3	4.6	382.3	83.1	5.4	1 187.1	219.8	3.4	269.3	79.2
Mexico	1.2	339.1	282.6	1.2	2 492.9	2 077.5	1.0	107.4	107.4	1.2	466.9	389.1	0.8	131.9	164.9
Spain	1.8	162.3	90.1	2.0	1 266.8	633.4	2.0	227.1	113.6	2.0	971.5	485.8	2.0	1 058.9	529.5
Sweden	8.6	337.7	39.3	9.0	8 111.6	901.3	8.8	1 013.5	115.2	9.0	4 502.6	500.3	6.6	2 416.0	366.1
Switzerland	2.0	150.6	75.3	2.0	386.0	193.0	1.6	101.2	63.2	2.0	282.1	141.1	1.8	739.1	410.6
HWR															
Canada	14	2 008	28.6	14	30 834	440	14	6 146	87.8	14	16 986	243	14	21 143	302
LWGR															
Lithuania	2.0	451.9	226.0	1.6	1 267.9	792.5	1.6	125.2	78.3	1.6	1 210.9	756.83	1.6	3 635.3	2 272.1
PWR															
Armenia							0.2	6.4	32.2	0.3	43.9	175.4	0.2	16.4	81.8
Belgium	6.2	417.8	67.4	6.2	1 809.7	291.9	5.8	288.1	49.7	6.0	763.1	127.2	4.6	419.1	91.1
China	2.0	136.0	68.0	2.0	444.2	222.1	1.0	15.8	15.8	2.0	269.8	134.9	1.4	134.3	95.9
Finland	2.0	69.5	34.7	2.0	441.8	220.9				2.0	359.8	179.9	0.8	87.7	109.6
France	46.8	5 295.1	113.1	46.8	25 087.7	536.1	46.0	3 257.6	70.8	46.6	13 398.6	287.5	46.0	5 118.3	111.3
Germany	9.2	579.2	63.0	10.6	4 872.9	459.7	6.2	810.2	130.7	8.8	2 552.6	290.1	4.4	688.2	156.4
Hungary	4.0	234.0	58.5	4.0	1 139.9	285.0				4.0	704.2	176.0	4.0	354.5	88.6
Netherlands	1.0	95.9	95.9	1.0	252.9	252.9	1.0	135.9	135.9	1.0	247.7	247.7	1.0	45.0	45.0
South Africa	1.6	111.2	69.5	1.6	522.9	326.8	1.4	57.1	40.8	1.6	248.4	155.3	0.8	19.7	24.6
Slovenia	1.0	179.5	179.5	1.0	685.3	685.3	0.8	21.1	26.4	1.0	205.7	205.7	0.8	11.1	13.9
Spain	5.6	723.9	129.3	5.6	2 179.6	389.2	5.6	326.6	58.3	5.6	1 353.1	241.6	0.8	128.3	160.4
Sweden	3.0	201.5	67.2	3.0	980.7	326.9	2.2	37.2	16.9	3.0	290.2	96.7	0.4	0.6	1.6

Switzerland	2.6	258.2	99.3	2.6	469.7	180.7	1.6	61.6	38.5	2.6	282.0	108.5	1.8	200.8	111.6
United Kingdom	0.6	49.9	83.2	1.0	119.5	119.5	0.6	16.7	27.8	1.0	53.8	53.8	1.0	68.1	68.1
2000–2003															
BWR															
Finland	1.5	40.8	27.2	1.8	290.5	166.0	1.8	121.1	69.2	1.5	189.8	126.6			
Germany	5.5	273.1	49.7	6.0	1 224.1	204.0	4.5	324.1	72.0	5.3	760.0	144.8	2.5	348.6	139.5
Mexico	1.3	282.5	226.0	1.3	2 100.8	1 680.6	1.3	48.5	38.8	1.3	410.8	328.6			
Spain	1.3	144.2	115.4	1.3	1 085.1	868.1	1.3	188.6	150.9	1.3	435.5	348.4	1.3	449.8	359.8
Sweden	7.3	286.3	39.5	7.3	3 254.3	448.9	7.3	311.5	43.0	8.0	2 223.2	277.9	6.5	1 622.0	249.5
Switzerland	2.0	103.3	51.6	2.0	110.2	55.1	1.5	126.9	84.6	1.5	354.9	236.6	0.3	8.6	34.5
HWR															
Canada	14	1 069	19.0	14	23 483	419	14	4 550	81.3	14	14 195	254	14	28 126	502
PWR															
Armenia	0.8	57.0	75.9	1.0	235.0	235.0	0.8	49.9	66.5	1.0	149.7	149.7	1.0	178.2	178.2
Belgium	6.3	182.1	29.1	6.3	921.9	147.5	6.3	192.7	30.8	6.3	471.2	75.4	5.0	215.6	43.1
Brazil	1.5	227.0	151.3	1.5	486.8	324.5	1.0	50.8	50.8	1.5	288.6	192.4	1.5	183.1	122.0
China	2.3	78.4	34.8	2.5	702.8	281.1	2.0	42.1	21.1	1.0	225.8	225.8	0.8	20.4	27.2
Czech Republic	2.0	2.2	1.1	2.0	236.3	118.2				2.0	474.4	237.2	1.5	72.3	48.2
Finland	2.0	83.4	41.7	2.0	169.5	84.7				4.0	686.1	171.5	4.0	949.7	237.4
France	47.3	2 708.1	57.3	47.3	13 891.9	294.0	47.3	3 821.4	80.9	47.3	9 712.0	205.6	46.0	296.6	6.5
Germany	11.0	726.5	66.1	11.8	2 828.5	240.7	8.3	1 034.8	125.4	10.5	1 886.4	179.7	3.5	57.2	16.4
Hungary	4.0	224.7	56.2	4.0	1 170.1	292.5									
Netherlands	1.0	14.3	14.3	1.0	76.7	76.7	0.8	4.1	5.5	1.0	64.0	64.0	0.3	16.3	65.0
Slovenia	1.0	138.2	138.2	1.0	306.5	306.5	1.0	24.9	24.9	1.0	86.4	86.4	0.3	63.9	255.5
South Africa	1.5	59.2	39.4	1.5	538.8	359.2	1.3	114.5	91.6	1.5	221.2	147.5	1.0	83.3	83.3
Spain	5.5	513.6	93.4	5.5	944.9	171.8	5.5	193.5	35.2	5.5	631.2	114.8	5.3	419.4	79.9
Sweden	3.0	178.6	59.5	3.0	845.7	281.9	3.0	81.1	27.0	3.0	237.6	79.2			
Switzerland	6.0	446.9	74.5	2.8	392.0	142.6	0.8	19.0	25.3	2.0	410.4	205.2	0.5	10.0	20.0
United Kingdom	1.0	49.4	49.4	1.0	116.8	116.8	0.8	5.6	7.5	1.0	63.3	63.3	1.0	96.0	96.0

a Refuelling: all activities related to refuelling, including the cleaning of the refuelling pool.

b Maintenance: work on reactor vessel or internals, steam generators, residual or shutdown heat removal system and safety injection system, chemical and volume control system, pressurizer, reactor water clean-up system, reactor coolant pumps, primary circuit, valves, steam system, recirculation system and coolant pump seal water system, control rod drives.

c Servicing: general work, scaffolding and insulation.

d Other: other work not listed above.

Table 68. Occupational exposure due to the decommissioning of 13 nuclear power plants in the United States
Data from the UNSCEAR Global Survey of Occupational Radiation Exposures

Period	*Measurably exposed workers (10^3)*	*Annual collective dose (man Sv)*	*Average annual effective dose (mSv)*
1995–1999	1.90	3.83	2.01
2000–2002	2.17	4.15	1.91

Table 69. Estimated worldwide levels of exposure due to fuel reprocessing
Data from the UNSCEAR Global Survey of Occupational Radiation Exposures

Period	*Monitored workers (10^3)*	*Annual collective effective dose (man Sv)*	*Average annual effective dose (mSv)*
1975–1979	8	53	7.1
1980–1984	9	46	4.9
1985–1989	17	36	2.5
1990–1994	45	67	1.5
1995–1999	59	61	1.1
2000–2002	76	68	0.9

Table 70. Estimated worldwide levels of exposure due to nuclear fuel cycle research
Data from the UNSCEAR Global Survey of Occupational Radiation Exposures

Period	*Monitored workers (10^3)*	*Annual collective effective dose (man Sv)*	*Average annual effective dose (mSv)*
1975–1979	120	170	1.4
1980–1984	130	150	1.1
1985–1989	130	100	0.8
1990–1994	120	90	0.8
1995–1999	96	37	0.4
2000–2002	90	36	0.4

Table 71. Occupational exposure due to radioactive waste management in the nuclear fuel cycle

Country	*Period*	*Monitored workers (10^3)*	*Measurably exposed workers (10^3)*	*Annual collective dose*	*Average annual effective dose (mSv)*		*Distribution ratio (number of workers)*			
				Total (man Sv)	*Monitored workers*	*Measurably exposed workers*	NR_{20}	NR_{10}	NR_5	NR_1
China[a]	1990–1994	1.51		5.33	3.53			0.09		
	1995–2000	1.30		4.03	3.10			0.08		
United Kingdom[b]	1995–1999	0.29		0.09	0.30					
	2000–2002	0.35		0.07	0.20					
United States[c]	1995–1999	8.05	1.90	1.22	0.15	0.65	0.00	0.00	0.00	0.04
	2000–2002	5.88	1.76	1.07	0.18	0.61	0.00	0.00	0.00	0.05

[a] Data from reference [T4].
[b] Data from reference [I38].
[c] Data from the UNSCEAR Global Survey of Occupational Radiation Exposures.

Table 72. Worldwide average annual exposures due to the commercial nuclear fuel cycle[a]

Practice	*Monitored workers[b] (10^3)*	*Average annual collective effective dose (man Sv)*	*Average annual collective effective dose per unit energy generated (man Sv/GW a)*	*Average annual effective dose to monitored workers (mSv)*	*Distribution ratio[c]*	
					NR_{15}[d]	SR_{15}
1975–1979						
Mining[e,f]	240	1 300	5.7	5.5	0.37	0.69
Milling[e,f]	12	124	0.5	10	0.41	0.76
Enrichment[e]	11	5	0.02	0.5	0.00	0.00
Fuel fabrication	20	36	0.6	1.8	0.012	0.38[g]
Reactor operation	150	600	11.0	4.1	0.078[h]	0.60[i]
Reprocessing[j]	78	53	0.7	7.1	0.16	0.29
Research	120	170	1.0	1.4	0.035	0.42
Total	560	2 300	20	4.4	0.20	0.63
1980–1984						
Mining[e,f]	310	1 600	5.5	5.1	0.30	0.61
Milling[e,f]	23	117	0.4	5.1	0.30	0.64
Enrichment[e]	4	1	0.02	0.2	0.00	0.00
Fuel fabrication	21	21	0.2	1.0	0.002	0.11[g]
Reactor operation	290	1 000	10.0	3.6	0.069[h]	0.52[i]
Reprocessing[j]	9	46	0.8	4.9	0.10	0.39
Research	130	150	1.0	1.1	0.021	
Total	800	3 000	18	3.7	0.16	
1985–1989						
Mining[e,f]	260	1 100	4.3	4.4	0.25	0.52
Milling[e,f]	18	116	0.4	6.3	0.18	0.43
Enrichment[e]	5.0	0.4	0.02	0.1	0.00	0.00
Fuel fabrication	28	22	0.1	0.8	0.002	0.019[g]
Reactor operation	430	1 100	5.7	2.5	0.033[h]	0.34[i]
Reprocessing[j]	17	36	0.7	3.0	0.064	0.12[j]
Research	130	100	1.0	0.8	0.011	0.30
Total	888	2 500	12	2.6	0.10	0.42

Practice	*Monitored workers*[b] *(10^3)*	*Average annual collective effective dose (man Sv)*	*Average annual collective effective dose per unit energy generated (man Sv/GW a)*	*Average annual effective dose to monitored workers (mSv)*	*Distribution ratio*[c]	
					NR_{15}[d]	SR_{15}
1990–1994						
Mining[e,f]	69 (62)	310	1.7	4.5 (5.0)	0.10	0.32
Milling[e,f]	6	20	0.1	3.3	0.00	0.01
Enrichment[e]	13	1	0.02	0.1	0.00	0.00
Fuel fabrication	21 (11)	22	0.1	1.0 (2.0)	0.01	0.11
Reactor operation	530 (300)	900	3.9	1.4 (2.7)	0.00[h]	0.08
Reprocessing[j,k]	45 (24)	67	3.0	1.5 (2.8)	0.00	0.13
Research	120 (36)	90	1.0	0.8 (2.5)	0.00	0.22
Total	800 (450)	1 400	9.8	1.8 (3.1)	0.01	0.11
1995–1999						
Mining[e,f]	22	85	0.5	3.9	0.04	0.14
Milling[e,f]	3	4	0.03	1.6		
Enrichment[e]	17	1	0.02	0.1	0.00	0.00
Fuel fabrication	22	30	0.1	1.4	0.00	0.01
Reactor operation	448	779	2.5	1.5	0.00	0.03
Reprocessing[j,k]	59	61		1.1		
Research	96	37	1	0.4	0.01	0.22
Total	700	1 000	1	1.4	0.01	0.07
2000–2002						
Mining[e,f]	12	22	0.1	1.9	0.05	0.14
Milling[e,f]	3	3	0.02	1.1		
Enrichment[e]	18	2	0.02	0.1	0.00	0.00
Fuel fabrication	20	31	0.1	1.6	0.01	0.01
Reactor operation	437	617	2.5	1.0	0.02	0.13
Reprocessing[j,k]	76	68		0.9		
Research	90	36	1	0.4	0.01	0.02
Total	660	800	1	1.0	0.02	0.07

a Data are annual values averaged over the indicated periods.
b Data in parentheses are for measurably exposed workers.
c The values of the distribution ratios should be considered as only indicative of worldwide levels, as they are in general based on data from far fewer countries than the data for the number of workers and collective doses.

d Ratio applies to monitored workers.

e Also includes uranium obtained or processed for purposes other than the commercial nuclear fuel cycle.

f For 1985–1989 the data for mining and milling (except for NR and SR) have been modified from those reported by using a conversion factor of 5.6 mSv/WLM for exposure to radon daughters (10 mSv/WLM used in the reported data). The ratios NR_{15} and SR_{15} are averages of reported data in which, in general, the previously used conversion factor has been applied. The tabulated ratios are thus strictly for a value of E somewhat less than 15 mSv. The relationship between the reported and the revised data is not linear, because exposure occurs from other sources besides the inhalation of radon progeny. For 1990–1994 a conversion factor of 5.0 mSv/WLM for exposure to radon daughters has been used.

g Ratio applies to LWR and HWR fuels only, as data for other fuels are not available; the ratio would be smaller if all fuel types were included.

h Does not include data for LWGRs, FBRs and HTGRs.

i Does not include data for GCRs, LWGRs, FBRs and HTGRs.

j Also includes the reprocessing of some fuel from the defence nuclear fuel cycle.

k In the absence of sufficient data on equivalent electrical energy generated by reporting countries for 1990–1994, the Committee has taken the normalized average annual collective effective dose per unit energy generated to be the same as that for the previous period.

Table 73. Exposure of physicians during lung biopsy (mGy per minute of fluoroscopy) [N15]

Fluoroscopy conditions set	*A*		*B*	
Use of needle holder	*No*		*Yes*	
Physician	*Operating*	*Assisting*	*Operating*	*Assisting*
Corner of the eye, right	93 ± 44	15.0 ± 10.4	15.3 ± 2.9	2.54 ± 0.93
Corner of the eye, left	23 ± 14.8	4.9 ± 3.6	3.1 ± 0.48	1.23 ± 0.78
Neck (thyroid)	86 ± 46	15.2 ± 10.1	8.0 ± 1.02	2.3 ± 1.54
Upper arm, right	125 ± 68	21 ± 24	18.1 ± 6.2	2.4 ± 0.83
Upper arm, left	19.8 ± 11.9	7.8 ± 5.9	2.8 ± 2.5	1.27 ± 1.13
Back of the hand, right	10 900 ± 11 600	8.4 ± 7.5	240 ± 125	1.76 ± 0.99
Back of the hand, left	150 ± 117	6.6 ± 5.5	140 ± 0.08	1.10 ± 0.90
Fingers, right	2 600 ± 2 100	45 ± 80	84 ± 101	2.45 ± 1.02
Fingers, left	590 ± 400	4.2 ± 3.2	6.9 ± 0.53	1.66 ± 1.43
Back of the head	38 ± 20	5.2 ± 5.5	1.27 ± 1.05	0.79 ± 0.65
Back	4.2 ± 2.7	0.98 ± 1.05	2.4 ± 0.47	0.70 ± 0.20
Inside of femur	3.3 ± 3.0	2.3 ± 3.0	0.68 ± 0.40	0.85 ± 0.90
Chest, inside protector	7.6 ± 5.4	2.3 ± 2.9	0.94 ± 0.46	1.35 ± 1.50
Abdomen, insider protector	6.9 ± 4.6	1.23 ± 1.35	0.54 ± 0.54	0.76 ± 0.69
Chest, outside protector	66 ± 35	9.8 ± 8.5	9.0 ± 1.83	1.48 ± 0.97
Abdomen, outside protector	68 ± 39	7.9 ± 8.8	13.1 ± 2.2	1.11 ± 0.59

Table 74. Occupational doses incurred by primary medical doctors during interventional procedures [S21]

Procedure type (number of measurements)	*TLD position/ dosimetric quantity*	*Range of dose (mSv)*	*Average dose (mSv)*	*Average time of fluoroscopy (min)*	*Average number of frames*
Coronariography (n = 62)	Chest outside the apron/*Hp(10)*	0–2.35	0.29	7.8	991
	Chest inside the apron/*Hp(10)*	0–0.27	0.06		
	Right hand/*Hp(0.07)*	0–2.54	0.26		
	Left hand/*Hp(0.07)*	0–3.88	0.38		
	Knee/*Hp(0.07)*	0–1.61	0.21		
	Neck without collar/*Hp(10)*	0.18–2.88			
	Neck with collar/*Hp(10)*	0–0.27	0.13		
	Forehead/*Hp(3)*	0–0.82	0.14		
Angioplasty (n = 30)	Chest outside the apron/*Hp(10)*	0–0.18	0.04	13	762
	Chest inside the apron/*Hp(10)*	0–0.18	0.02		
	Right hand/*Hp(0.07)*	0–0.30	0.05		
	Left hand/*Hp(0.07)*	0–0.40	0.13		
	Knee/*Hp(0.07)*	0–0.72	0.10		
	Neck without collar/*Hp(10)*	0.14–0.27			
	Neck with collar/*Hp(10)*	0–0.14	0.07		
	Forehead/*Hp(3)*	0–0.33	0.05		
Arteriography (n = 4)	Chest outside the apron/*Hp(10)*	0–0.18	0.09	4	390
	Chest inside the apron/*Hp(10)*	0–0.13	0.07		
	Right hand/*Hp(0.07)*	0–0.18	0.05		
	Left hand/*Hp(0.07)*	0–0.65	0.16		
	Knee/*Hp(0.07)*	0–0.18	0.09		
	Neck without collar/*Hp(10)*	0.18–0.18			
	Neck with collar/*Hp(10)*	0–0	0.05		
	Forehead/*Hp(3)*	0–0	0.00		

Procedure type (number of measurements)	*TLD position/ dosimetric quantity*	*Range of dose (mSv)*	*Average dose (mSv)*	*Average time of fluoroscopy (min)*	*Average number of frames*
Valvuloplasty ($n = 5$)	Chest outside the apron/*Hp(10)*	0–0.18	0.04	16	225
	Chest inside the apron/*Hp(10)*	0–0.27	0.08		
	Right hand/*Hp(0.07)*	0–0	0.00		
	Left hand/*Hp(0.07)*	0–0.37	0.07		
	Knee/*Hp(0.07)*	0–0.34	0.12		
	Neck without collar/*Hp(10)*	0–0			
	Neck with collar/*Hp(10)*	0–0	0.00		
	Forehead/*Hp(3)*	0–0	0.00		

Table 75. Mean and maximum doses for the staff of the interventional cardiology (IC) and interventional radiology (IR) services of a university hospital [V9]

Year	*Professionals*	*Mean dose (mSv/a)*		*Maximum dose (mSv/month)*	
		Whole body (under the apron)	*Shoulder (on the apron)*	*Hand (wrist)*	*Shoulder*
1999	IC physicians	0.1	1.0	1.1	13.7
	IC fellows	0.3	2.3		
	IC nurses	0.2	0.9		
2000	IC physicians	0.2	0.7	1.3	18.8
	IC fellows	0.2	2.5		
	IC nurses	0.1	0.9		
2001	IC physicians	0.1	2.0	9.3	10.5
	IC fellows	0.3	2.6		
	IC nurses	0.1	1.0		
1999	IR physicians	0.1	2.7	2.9	5.8
	IR technicians	0.1	0.4		
2000	IR physicians	0.1	2.1	3.2	7.1
	IR technicians	0.1	0.2		
2001	IR physicians	0.1	2.1	3.6	3.5
	IR technicians	0.1	0.4		

Table 76. Dose per procedure in vascular interventional radiology, measured by TLD [V7]

TLD location	*Sample size*	*Average dose (μSv)*	*Median dose (μSv)*	*Range (μSv)*
Left shoulder	21	283	182	45–1 214
Right eye	18	296	122	45–2 103
Left eye	19	284	95	40–1 683
Forehead	19	222	159	19–1 013
Neck	19	325	138	48–2 104
Right hand	23	260	120	47–974
Left hand	23	396	184	40–2 150
Left forearm	22	326	225	40–1 886
Arm	29	365	243	50–1 068

Table 77. Dose per procedure in interventional cardiology, measured by TLD [V7]

TLD location	*Sample size*	*Average dose (μSv)*	*Median dose (μSv)*	*Range (μSv)*
Average of doses with and without lead screen				
Left shoulder	55	252	185	30–1 031
Right eye	53	167	140	39–742
Left eye	54	294	193	53–1 005
Forehead	53	236	178	40–934
Neck	54	269	214	43–816
Right hand	54	191	144	45–921
Left hand	58	364	256	60–1 500
Left forearm	54	646	445	88–2 890
Arm	54	618	414	70–1 919
With lead screen				
Left shoulder	29	136	145	30–250
Right eye	29	136	140	52–252
Left eye	29	170	148	53–460
Forehead	29	145	150	40–415
Neck	29	163	160	43–398
Right hand	28	147	128	45–466
Left hand	31	235	195	60–740
Left forearm	29	440	350	88–2 890
Arm	30	265	237	70–727
Without lead screen				
Left shoulder	26	382	308	125–1 031
Right eye	24	205	138	39–742
Left eye	25	439	425	158–1 005
Forehead	26	344	330	103–934
Neck	27	392	389	60–816
Right hand	25	242	149	45–921
Left hand	25	514	372	65–1 500
Left forearm	25	885	801	168–2 006
Arm	24	1 061	1 027	108–1 919

Table 78. Occupational doses associated with specific interventional procedures

Dose per procedure (mSv)	*Procedure type*	*X-ray system*	*Relevant exposure parameters*	*Protection tools used*	*Reference*
0.215–0.370 (at thyroid level)	Coronary angiography	Philips Polydiagnost C2	2.8–3.4 min fluoroscopy, 637–1 058 frames	Ceiling-mounted screen, 1 mm lead	[S37]
0.008–0.113 (forehead)	Cardiac catheterization	Three centres, five X-ray units	2–3 min fluoroscopy, 500–2 000 frames, 4 400 cGy/cm^2	Ceiling-mounted screen, protective eye shields (reduction in exposure rate by a factor of about 20)	[P12]
0.05–0.14 (neck)	Vascular and liver	Philips Integris 3000 GE L-U	5 400–6 700 cGy/cm^2	Ceiling-mounted screen in only one room	[W15]
0.28 (left eye), 0.20 (thyroid)	Cardiac catheter ablation	Siemens Angioskop D	44 min fluoroscopy	Ceiling-mounted screen	[C1]
0.05 (collar level)	Coronariography and PTCA	Philips Integris 3000 DC	6 600 cGy/cm^2	Movable shield	[Z6]

Dose per procedure (mSv)	*Procedure type*	*X-ray system*	*Relevant exposure parameters*	*Protection tools used*	*Reference*
0.43 (forehead, eye)	Coronary angiography and PTCA	14 laboratories	Cine 53 s, fluoroscopy 6.8 min	Protective eyeglasses	[K3]
0.014 (eye)	Cerebral angiography, arterial embolization	CGR DG 300	4 850 cGy/cm^2, 12 220 cGy/cm^2	Waist-height lead shield	[M10]
1–2 (eye)	Interventional radiology	General Electric Phasix 80	10 images, 10 min fluoroscopy	No ceiling-mounted screen; lead apron and gloves	[V8]

Table 79. Worldwide levels of occupational exposure due to diagnostic radiology
Data from the UNSCEAR Global Survey of Occupational Radiation Exposures

Period	*Monitored workers (10^3)*	*Measurably exposed workers (10^3)*	*Annual collective effective dose (man Sv)*	*Average annual effective dose (mSv)*	
				Monitored workers	*Measurably exposed workers*
1975–1979	630		600	0.9	
1980–1984	1 060		720	0.7	
1985–1989	1 350		760	0.6	
1990–1994	950	350	470	0.5	1.3
1995–1999	6 670		3 300	0.5	
2000–2002	6 670		3 300	0.5	

Table 80. Worldwide levels of occupational exposure due to dental practice
Data from the UNSCEAR Global Survey of Occupational Radiation Exposures

Period	*Monitored workers (10^3)*	*Measurably exposed workers (10^3)*	*Annual collective effective dose (man Sv)*	*Average annual effective dose (mSv)*	
				Monitored workers	*Measurably exposed workers*
1975–1979	370		120	0.32	
1980–1984	500		93	0.20	
1985–1989	480		25	0.05	
1990–1994	265	17	16	0.06	0.89
1995–1999	404		24	0.06	
2000–2002	404		24	0.06	

Table 81. Annual doses incurred by PET workers [Z5]

Worker	*Effective dose (mSv)*	*Equivalent dose to hands (mSv)*	*Film monthly dose range (mSv)*	*Ring monthly dose range (mSv)*
Technologist 1	8.0	90.0	0.4–1.1	4.1–9.9
Technologist 2	4.6	63.5	0.3–0.7	0.7–9.1
Physician 1	2.2	5.2	0.1–0.7	0.2–1.2
Physician 2	1.9	6.0	0.1–0.7	0.3–4.2

Table 82. Occupational doses (μSv) for various tasks, different patients and different technologists
Each patient was administered 555 MBq of ^{18}F FDG [M17]

	Patient 1 Technologist A	*Patient 2 Technologist A*	*Patient 3 Technologist B*	*Patient 4 Technologist B*
	PC C[c]	*PC A*[a]	*PC A*[a]	*PC B*[b]
Measure dosage	1.4	0.2	4.0	2.4
Carry dosage	0.1	0.0	0.1	0.9
Inject	1.8	0.7[d]	1.9	3.9
Escort to waiting area	0.5	0.8	0.0	1.8
Interview	1.8	0.0	0.0	0.7
Escort to imaging lab	1.4	0.3	0.5	0.5
Position	2.0	3.4	1.2	6.8
Reposition after 1 h	0.0	0.0	0.0	1.1
Exit	0.2	0.0	0.0	0.8
Total	9.2	5.4	7.7	18.9

[a] PC A: patient fully ambulatory and able to follow instructions.
[b] PC B: patient haltingly ambulatory, occasionally in a wheelchair.
[c] PC C: patient confined to a wheelchair, able to follow instructions with physical assistance.
[d] Physician performed injection.

Table 83. Occupational exposures due to the use of different types of scan [W11]

Scan	*Isotope*	*Number of patients*	*Median administered activity (MBq)*	*Median time post-injection (h)*	*Median exposure (μSv/h) for distance*			
					2 m	*1 m*	*0.5 m*	*0 m*
PET	^{18}F	41	57.4	1.1	2.0	5.2	14.1	71.0
Bone	Tc-MDP	57	760.2	3.5	1.8	3.4	9.0	43.0
LVEF[a]	Tc-RBC	23	900.0	0.3	3.0	8.0	21.0	144.0
Thallium	^{201}Tl	28	250.0	1.0	1.1	1.9	5.2	28.0
Renal	Tc-DTPA	33	389.6	2.0	1.0	2.1	4.6	23.0
Gallium	^{67}Ga	38	400.0	120.0	0.9	1.6	4.2	19.1
Cardiac	Sestamibi	31	900.0	1.0	4.1	9.4	19.3	110.3

[a] Left ventricular ejection fraction.

Table 84. Maximum daily dose to skin of the hands during radiosynoviorthesis [B9]

Measurement cycle	*Maximum daily dose Hp(0.07) (mSv)*			*^{90}Y administered (MBq)*	*Specific dose (μSv/MBq)*
	Preparation	*Application*	*Assistance*		
A-1[a]	82	43	5	805	53
A-2	101	132	10	1 675	79
A-3	16	16	2	620	26
A-4	18	33	Not measured	1 480	22
A-5	Not measured	1[b]	Not measured	555	1.8
A-6	Not measured	1[b]	Not measured	1 110	0.9
B-1	108	27	Not measured	2 035	13
C-1	14	41	Not measured	555	74
F-1	7	62	9	460	135
F-2	8	1[b]	36	2 005	0.5
G-1	15	5	1	180	28
G-2	4	11	2	360	31
H-1	55	207	None	888	233
I-1	8	31 (Doctor 1)	None	1 332	23
I-2	Not measured	84 (Doctor 2)	None	2 442	34
I-3	6	1[b] (Doctor 1)	None	1 554	0.6
I-4	Not measured	1[b] (Doctor 2)	None	1 332	0.8

[a] Seven different institutions.
[b] Use of forceps during application of radionuclides.

Table 85. Worldwide levels of occupational exposure in nuclear medicine
Data from the UNSCEAR Global Survey of Occupational Radiation Exposures

Period	*Monitored workers (10^3)*	*Measurably exposed workers (10^3)*	*Annual collective effective dose (man Sv)*	*Average annual effective dose (mSv)*	
				Monitored workers	*Measurably exposed workers*
1975–1979	61		62	1.0	
1980–1984	81		85	1.0	
1985–1989	90		85	1.0	
1990–1994	115	65	90	0.8	1.4
1995–1999	117		89	0.8	
2000–2002	120		87	0.7	

Table 86. Mean dose per application of ^{125}I in prostate using afterloading technique, and annual effective dose incurred by staff at various distances from the source [G4]

Staff	*μSv per application (annual) for distance*			
	0.5 m	*1 m*	*2 m*	*3 m*
Physicians	15 (1 200)	4.3 (347)	0.2 (13)	0.06 (4.8)
Physicist		4.3 (347)	1.3 (104)	
Nurses	15 (1 200)	4.3 (347)	0.2 (14)	0.06 (4.8)
Assistants				0.06 (4.8)

Table 87. Worldwide levels of occupational exposure in radiotherapy
Data from the UNSCEAR Global Survey of Occupational Radiation Exposures

Period	*Monitored workers (10^3)*	*Measurably exposed workers (10^3)*	*Annual collective effective dose (man Sv)*	*Average annual effective dose (mSv)*	
				Monitored workers	*Measurably exposed workers*
1975–1979	84		190	2.2	
1980–1984	110		180	1.6	
1985–1989	110		100	0.9	
1990–1994	120	48	65	0.6	1.3
1995–1999	264		132	0.5	
2000–2002	264		132	0.5	

Table 88. Trends of occupational exposure in all medical uses
Data from the UNSCEAR Global Survey of Occupational Radiation Exposures

Period	*Monitored workers (10^3)*	*Measurably exposed workers (10^3)*	*Annual collective effective dose (man Sv)*	*Average annual effective dose (mSv)*	
				Monitored workers	*Measurably exposed workers*
1975–1979	1 280	650	993	0.8	1.5
1980–1984	1 890	520	1 140	0.6	1.7
1985–1989	2 220	590	1 030	0.5	1.7
1990–1994	2 320	550	760	0.3	1.4
1995–1999	7 440		3 540	0.5	
2000–2002	7 440		3 540	0.5	

Table 89. Occupational exposure in industrial radiography in the United States [U29, U30, U31, U32, U33, U34, U36, U37]

Year	*Multiple-location*					*Single-location*				
	Monitored workers	*Measurably exposed workers*	*Annual collective effective dose (man Sv)*	*Average annual effective dose (mSv)*		*Monitored workers*	*Measurably exposed workers*	*Annual collective effective dose (man Sv)*	*Average annual effective dose (mSv)*	
				Monitored workers	*Measurably exposed workers*				*Monitored workers*	*Measurably exposed workers*
1995	3 245	2 404	13.32	4.10	5.54	285	61	0.06	0.21	0.99
1996	3 340	2 477	13.75	4.12	5.55	291	60	0.10	0.35	1.67
1997	3 140	2 370	12.81	4.08	5.40	296	84	0.10	0.34	1.19
1998	4 571	3 355	18.51	4.05	5.52	369	84	0.08	0.22	0.95
1999	3 571	2 777	15.44	4.32	5.56	266	50	0.07	0.26	1.41
2000	3 029	2 399	14.80	4.89	6.17	258	78	0.08	0.31	1.01
2001	3 522	3 082	21.05	5.98	6.83	256	79	0.06	0.23	0.75
2002	3 292	2 773	17.19	5.22	6.20	112	55	0.04	0.40	0.81
1995–1999	3 573	2 677	14.77	4.13	5.51	301	68	0.08	0.28	1.24
2000–2002	3 281	2 751	17.68	5.36	6.40	209	71	0.06	0.31	0.86

Table 90. Radiation dose to workers in a cyclotron and radiochemistry laboratory

As measured by national personnel monitoring service using $CaSO_4$:Dy TLD badges [P3]

Occupational exposure in cyclotron/ radiochemistry laboratory	*Whole-body dose (mSv)*	*Extremity (wrist) dose (mSv)*
Cyclotron	0.35	7.95
Cyclotron	0.85	0.45
Radiochemistry	0.60	4.45
Radiochemistry	1.80	3.4

Table 91. Global occupational exposures due to the nuclear fuel cycle and natural sources of radiation

Practice	*Monitored workers (10^3)*	*Average annual collective effective dose (man Sv)*	*Average annual effective dose to monitored workers (mSv)*
Nuclear fuel cycle			
1995–1999			
Mining	22	85	3.9
Milling	3	4	1.6
Enrichment	17	1	0.1
Fuel fabrication	22	30	1.4
Reactor operation	448	779	1.5
Reprocessing	59	61	1.1
Research	96	37	0.4
Total	670	1 000	1.4
2000–2002			
Mining	12	22	1.9
Milling	3	3	1.1
Enrichment	18	2	0.1
Fuel fabrication	20	28	1.6
Reactor operation	437	600	1.0
Reprocessing	76	68	0.9
Research	90	36	0.4
Total	660	800	1.0
Natural sources of radiation			
1995–1999 and 2000–2002			
Coal mining	6 900	16 560	2.4
Other mining	4 600	13 800	3.0
Workplaces other than mines	1 250	6 000	4.8
Aircrew	300	900	3.0
Total	13 050	37 260	2.9

Table 92. Global occupational exposures associated with man-made and natural sources of radiation

Source of exposure	*1975–1979*	*1980–1984*	*1985–1989*	*1990–1994*	*1995–1999*	*2000–2002*
Number of monitored workers (10^3)						
Natural radiation				6 500	13 050	13 050
Nuclear fuel cycle	560	800	888	800	670	660
Medical uses	1 280	1 890	2 220	2 320	7 440	7 440
Industrial uses	530	690	560	700	790	869
Military activities	310	350	400	420	378	331
Miscellaneous	140	180	160	360	476	565
Total (man-made)	2 820	3 910	4 228	4 600	9 754	9 865
Total	2 820	3 910	4 228	11 100	22 804	22 915
Annual collective effective dose (man Sv)						
Natural radiation				11 700	37 260	37 260
Nuclear fuel cycle	2 300	3 000	2 500	1 400	1 000	800
Medical uses	1 000	1 140	1 030	760	3 540	3 540
Industrial uses	870	940	510	360	315	289
Military activities	420	250	250	100	52	45
Miscellaneous	70	40	20	40	53	56
Total (man-made)	4 660	5 370	4 310	2 660	4 960	4 730
Total	4 660	5 370	4 310	14 360	42 220	41 990
Average annual effective dose (mSv)						
Natural radiation				1.8	2.9	2.9
Nuclear fuel cycle	4.4	3.7	2.6	1.8	1.4	1.0
Medical uses	0.8	0.6	0.5	0.3	0.5	0.5
Industrial uses	1.6	1.4	0.9	0.5	0.4	0.3
Military activities	1.3	0.7	0.7	0.2	0.1	0.1
Miscellaneous	0.5	0.3	0.2	0.1	0.1	0.1
Total (man-made)	1.7	1.3	1.0	0.6	0.5	0.4
Total	1.7	1.3	1.0	0.8	0.9	0.8

FIGURES

Figure I. Variation in solar activity in terms of the historical monthly average sunspot numbers during solar cycles [N4]

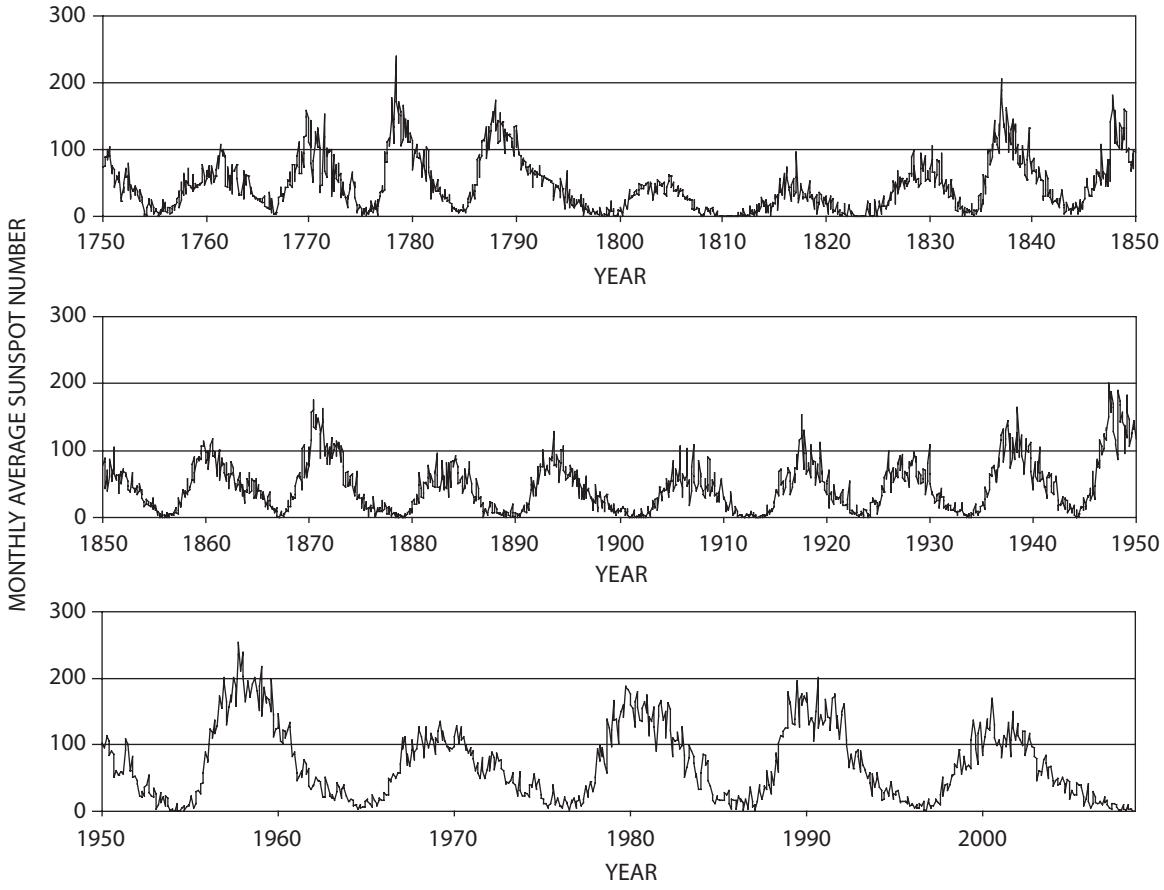


Figure II. Example of the influence of variation in solar activity on cosmic ray dose received during a return transcontinental flight between Frankfurt and New York City [S38]

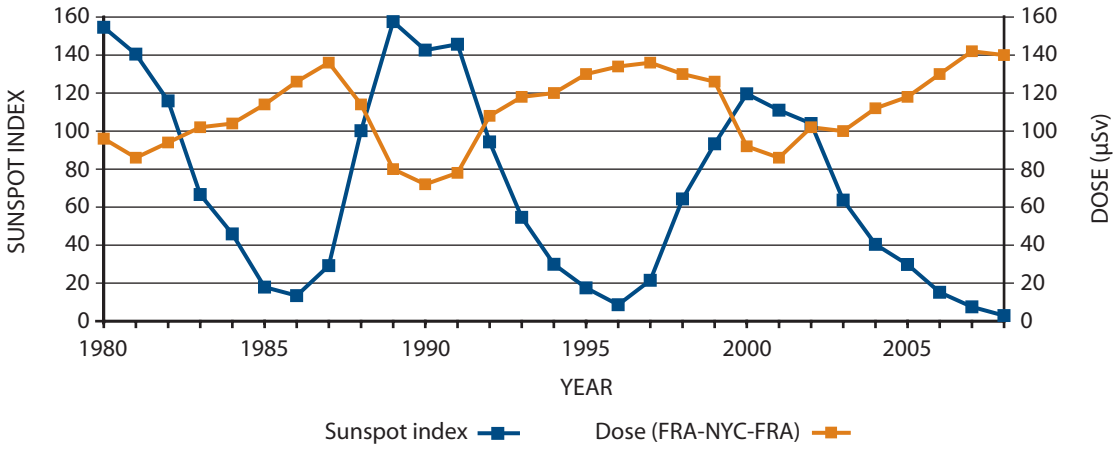


Figure III. Vertical cut-off rigidity, R_c (in GV), at 20 km altitude [S30]

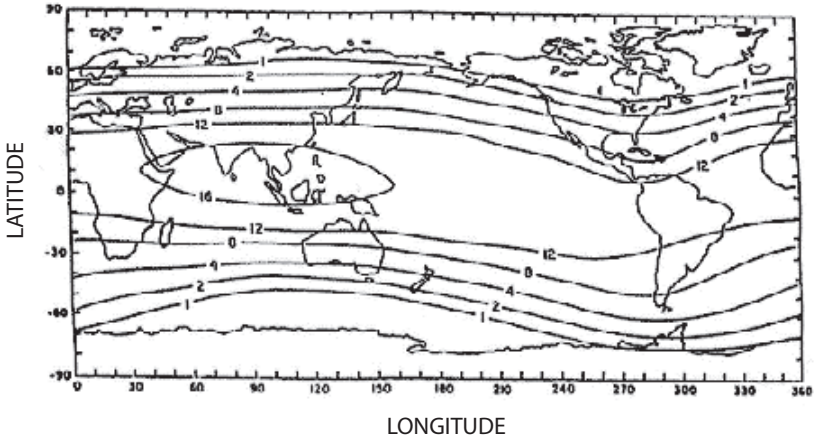


Figure IV. Components of the dose equivalent rate due to cosmic rays in the atmosphere [U3]

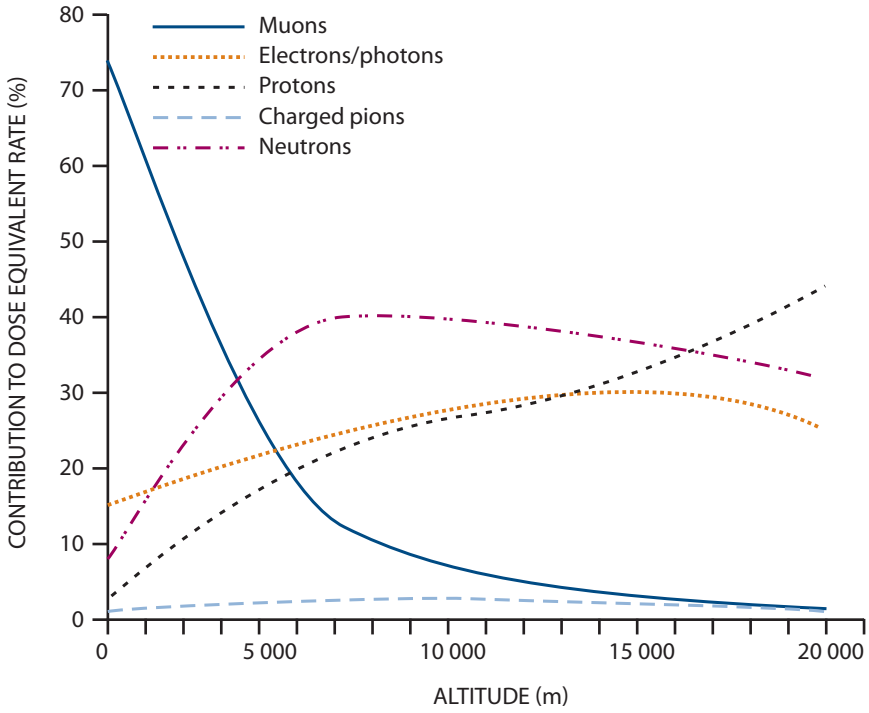
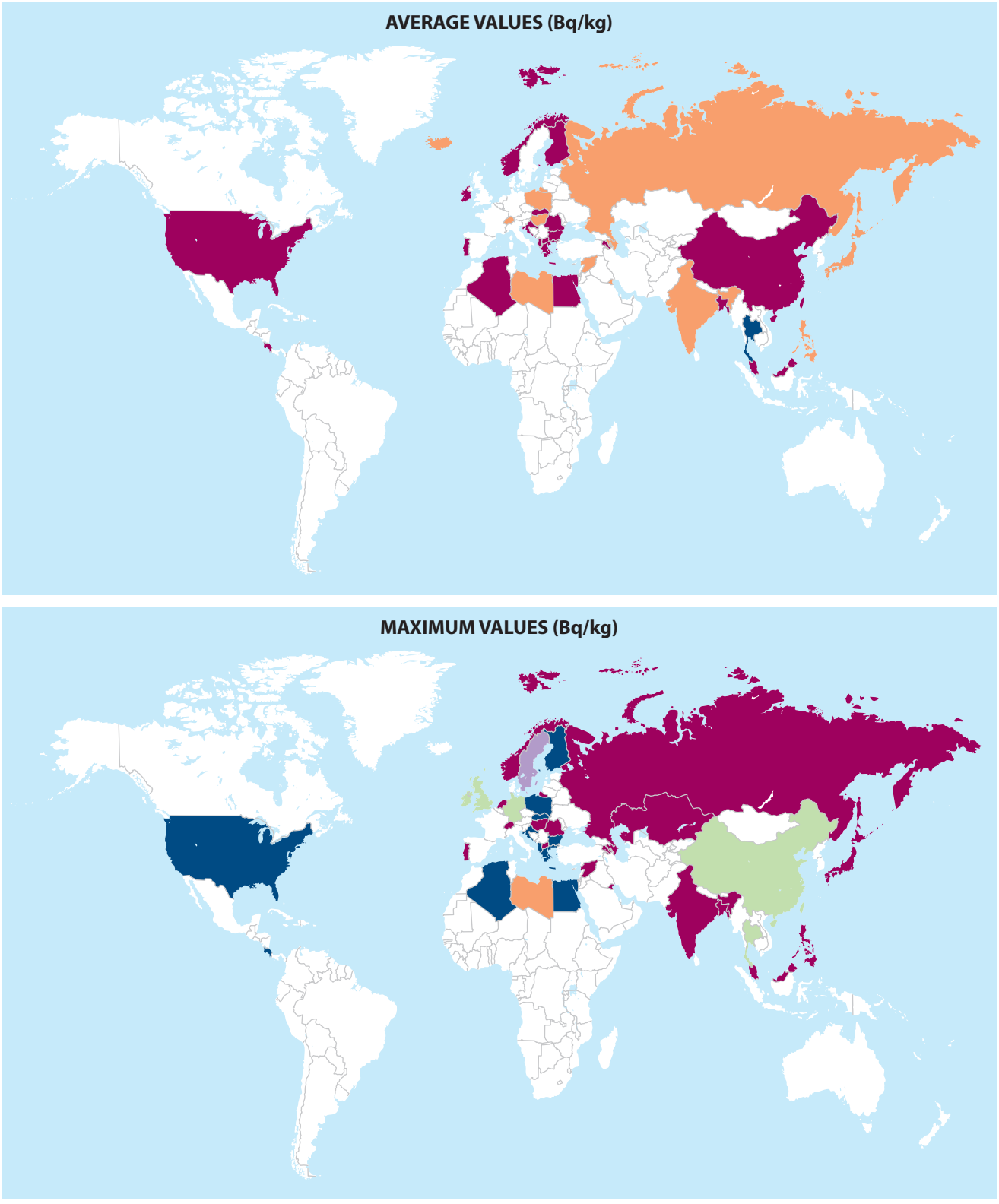


Figure V. Reported concentrations of ^{238}U in soil

Data from the UNSCEAR Global Survey on Exposures to Natural Radiation Sources



Data source: United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR)

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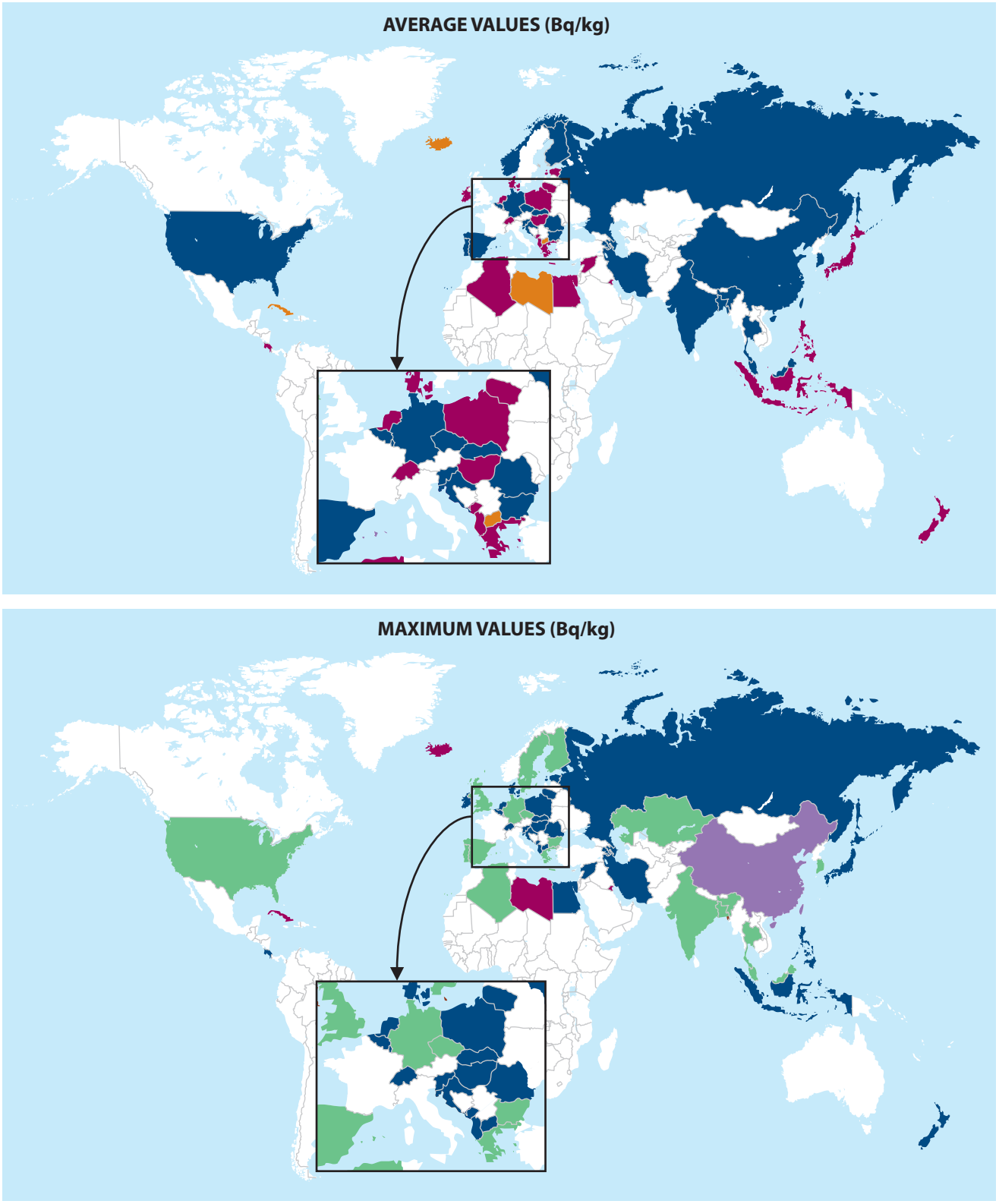
Figure VI. Reported concentrations of ^{232}Th in soil
Data from the UNSCEAR Global Survey on Exposures to Natural Radiation Sources



Data source: United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR)

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Figure VII. Reported concentrations of ^{40}K in soil

Data from the UNSCEAR Global Survey on Exposures to Natural Radiation Sources.

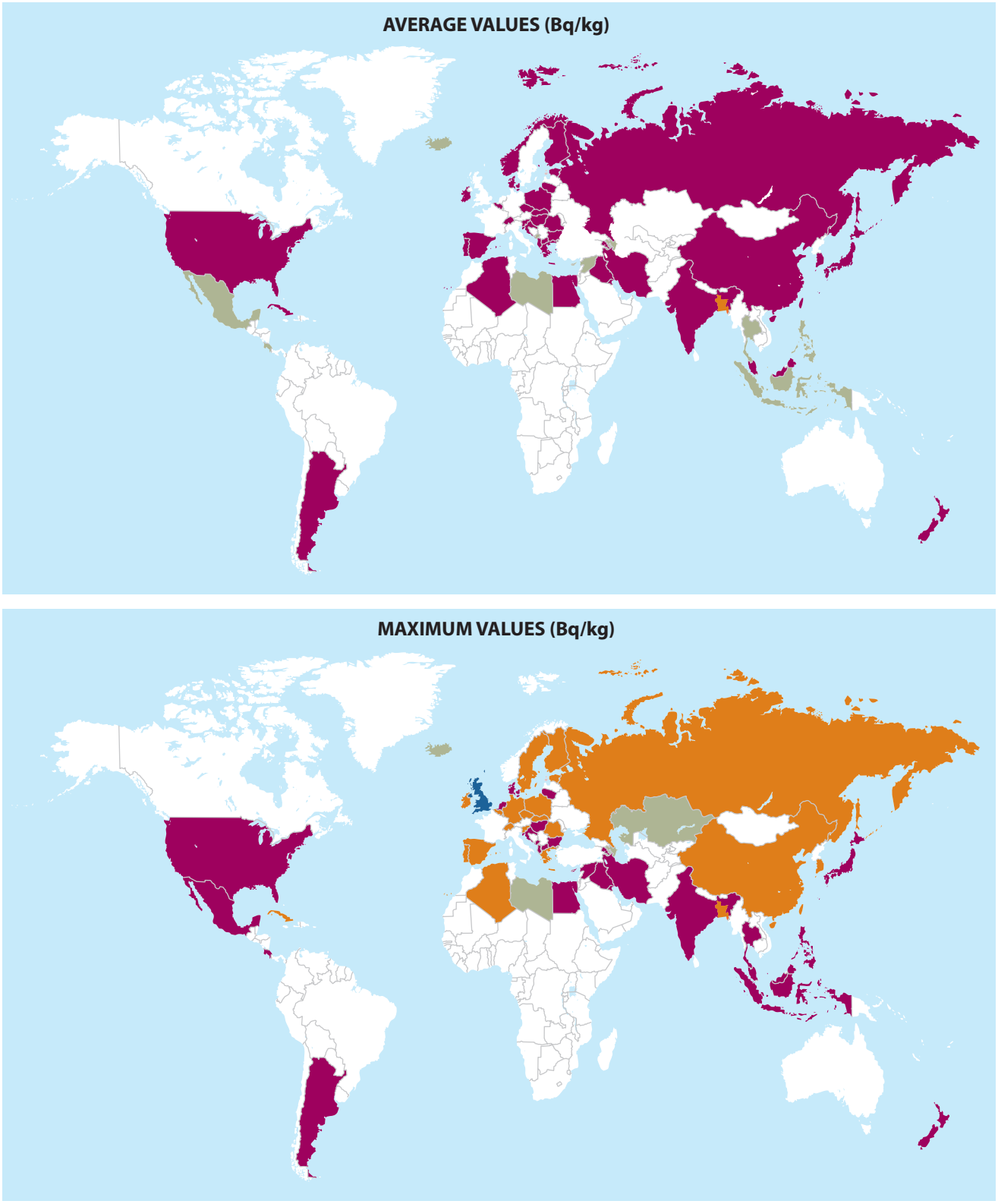

Figure VIII. Distribution of population with respect to ranges of absorbed dose rate in air
(Left: number of persons in each range; right: per cent cumulative distribution fraction for each range)

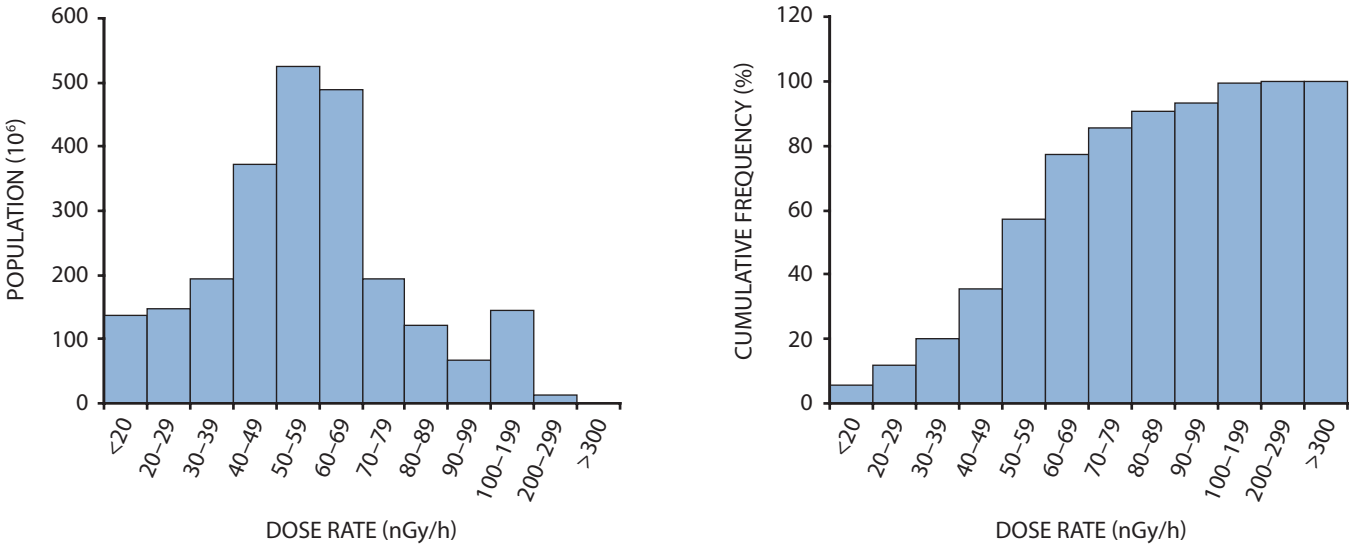

Figure IX. Reported ratios of $^{238}U/^{232}Th$ concentrations in soil
Data from the UNSCEAR Global Survey on Exposures to Natural Radiation Sources

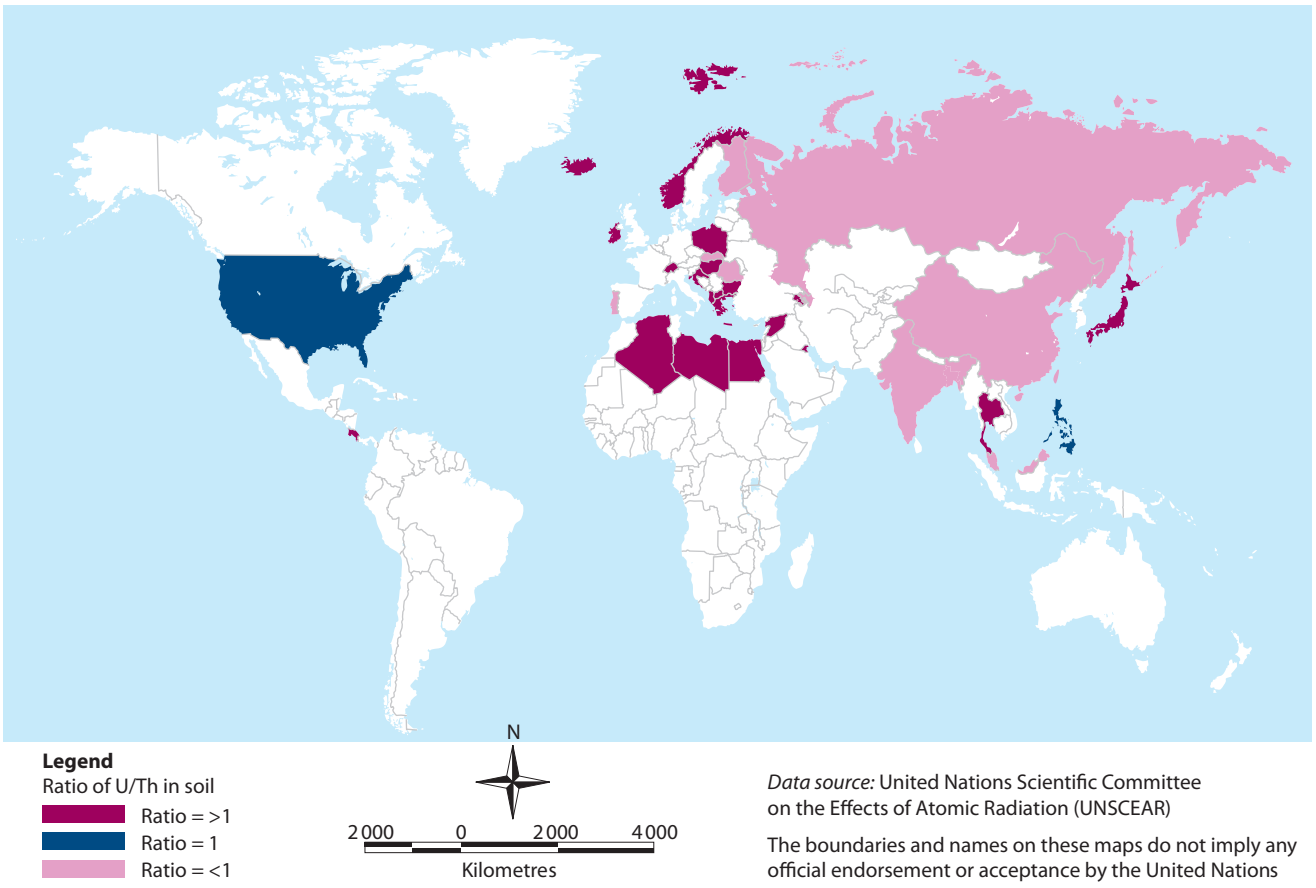

Figure X. Ranges of ^{238}U concentration in drinking water

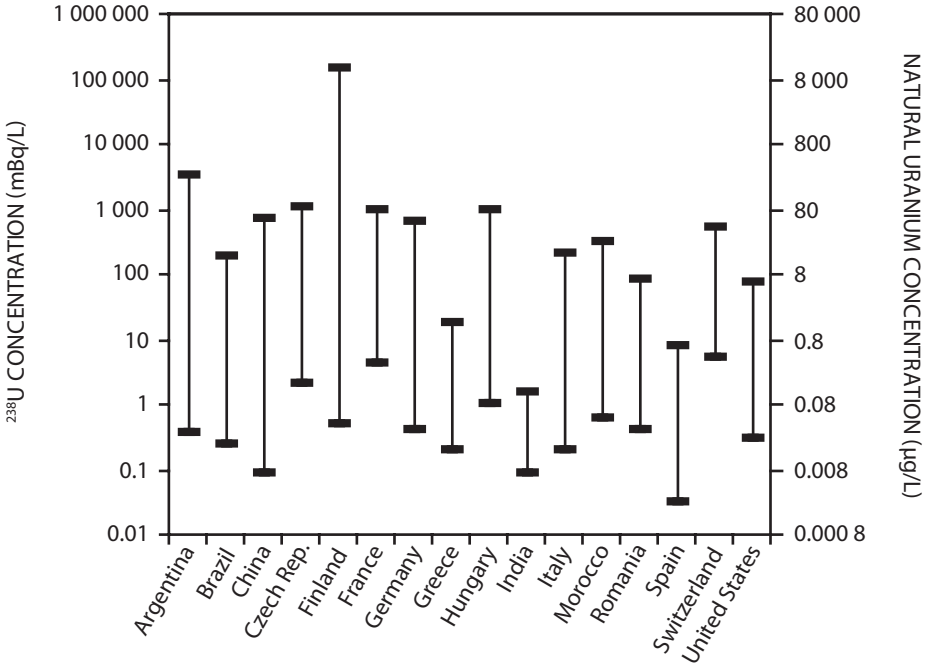

Figure XI. Cumulative frequency distribution of ^{238}U concentration in drinking water

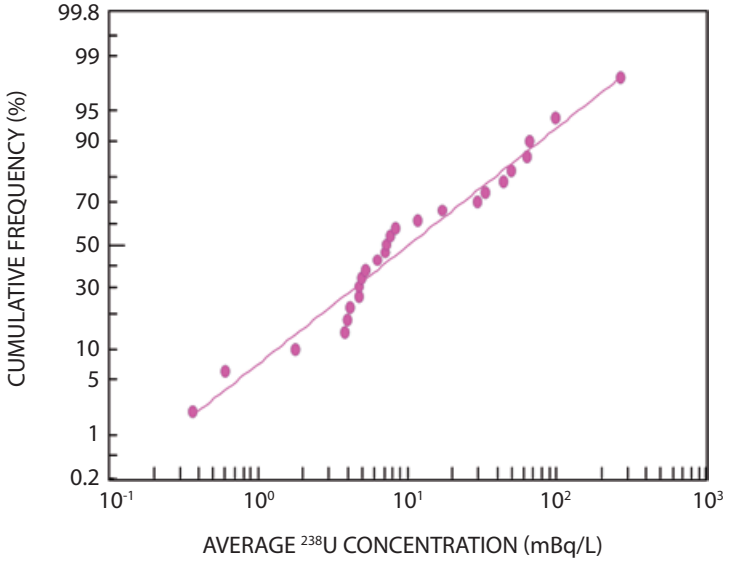

Figure XII. Cumulative frequency distribution of the concentrations in bone of radionuclides of the uranium and thorium series [U3]

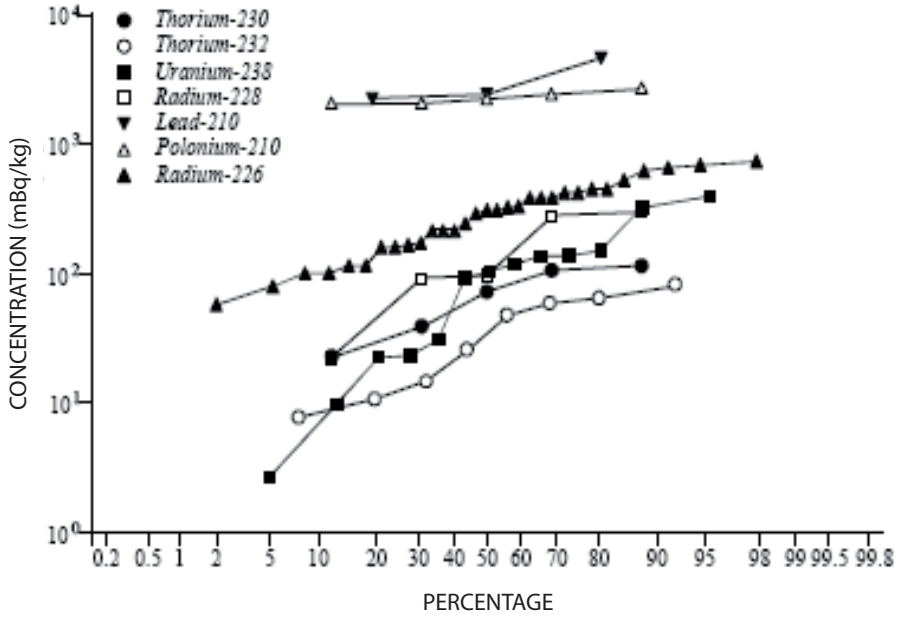

Figure XIII. Distribution of ^{210}Po in human body organs at steady state after chronic ingestion of radionuclides of the uranium and thorium series [C23, F8]

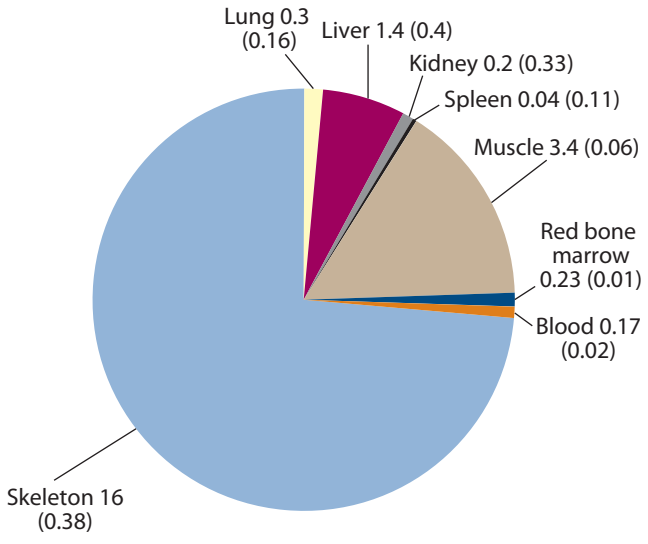

Figure XIV. Distribution of average radon concentrations in the indoor air of houses

Data from the UNSCEAR Global Survey on Exposures to Natural Radiation Sources and reference [D14]

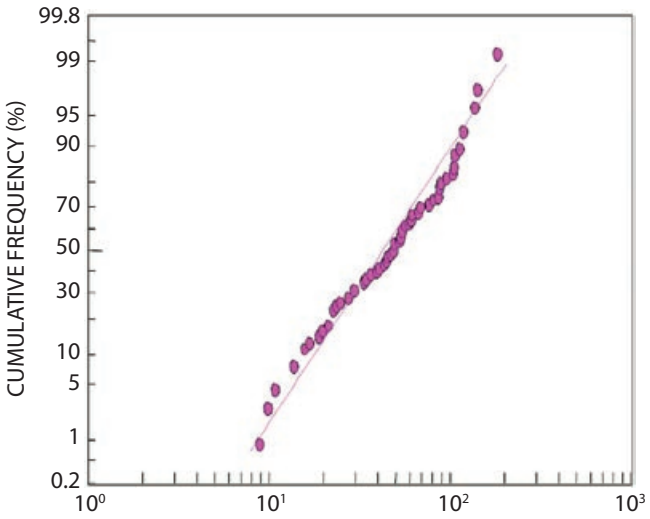

Figure XV. Total worldwide production of uranium (t) to 2003

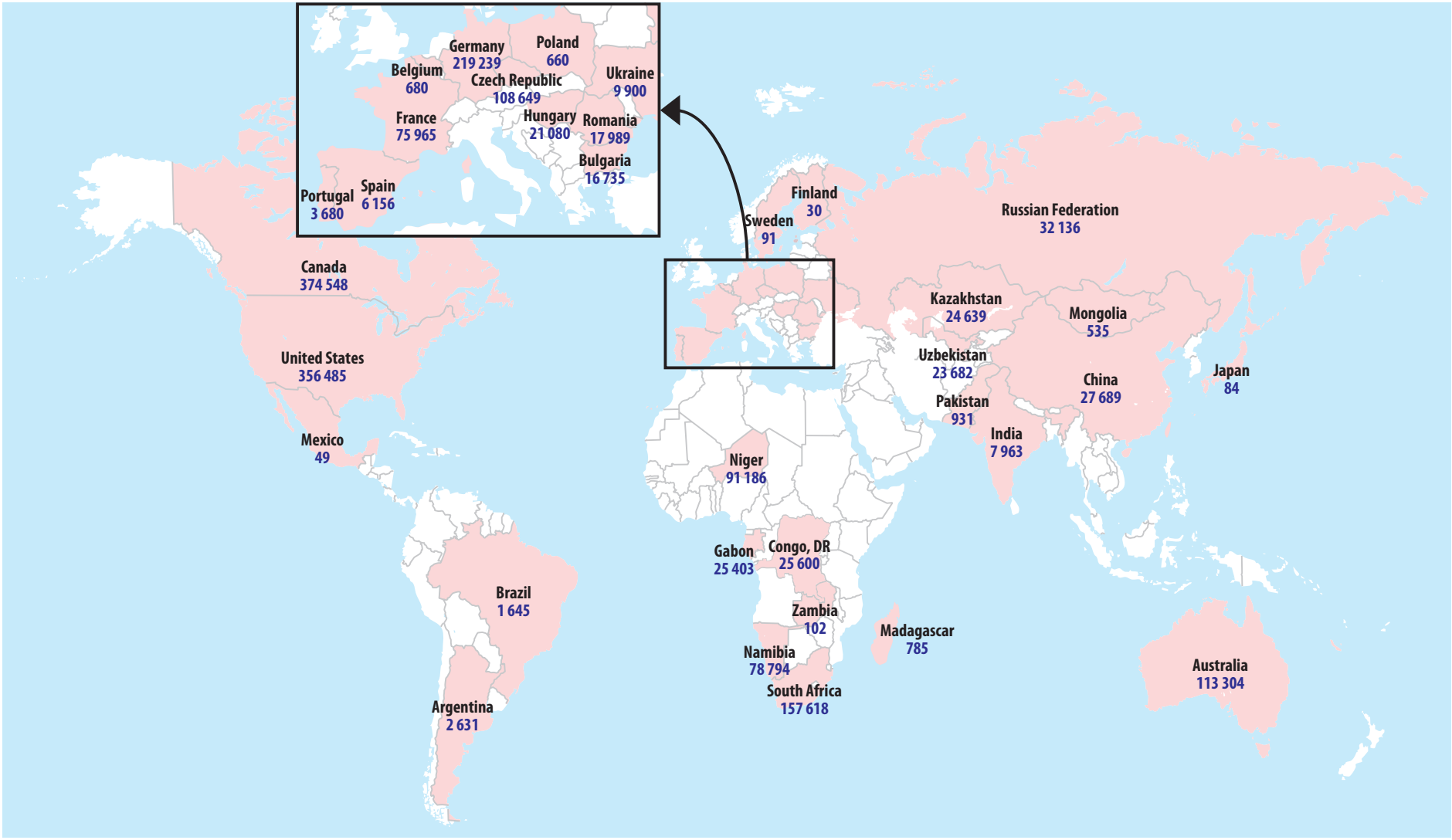

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Figure XVI. Annual uranium production from 1990 to 2003 [O16, O17, O21]

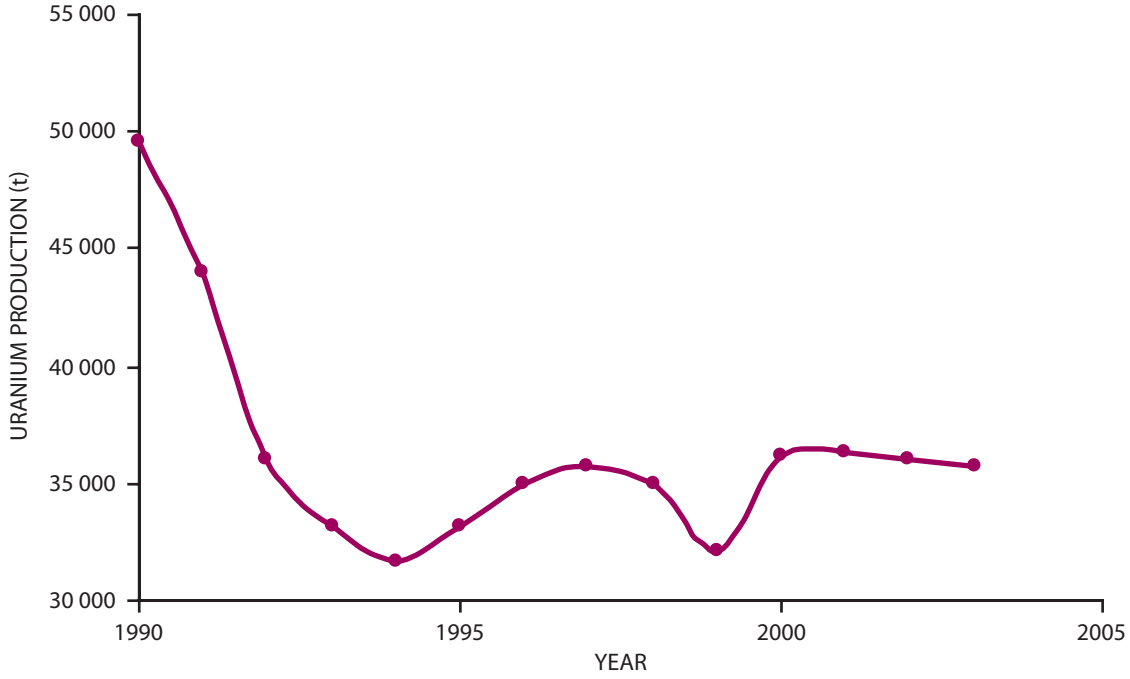

Figure XVII. Tailings from uranium mining and milling (10^6 t)

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Figure XVIII. Countries with facilities for production of nuclear fuel for power reactors

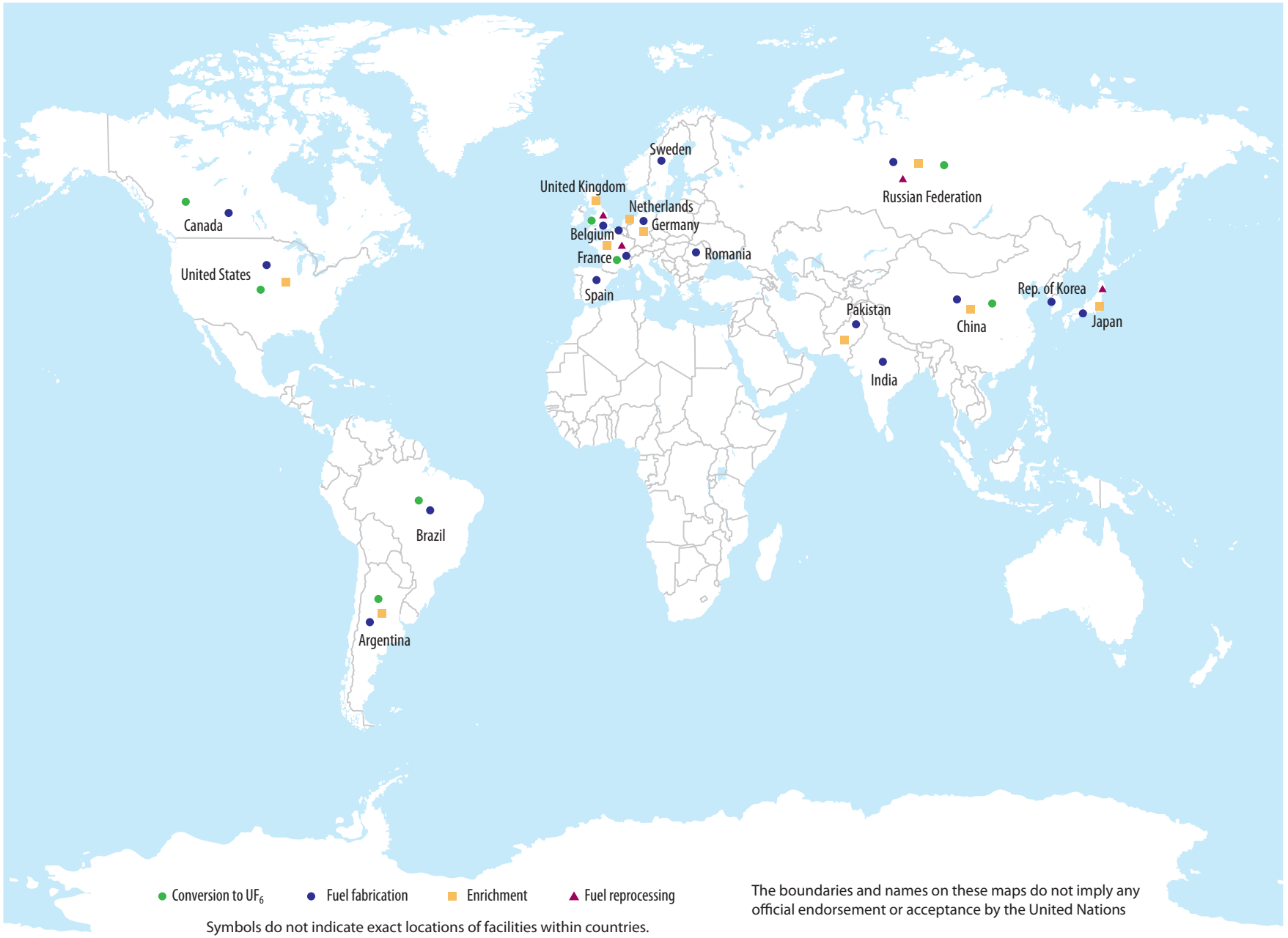

Figure XIX. Nuclear power reactors in the world, 1998–2002

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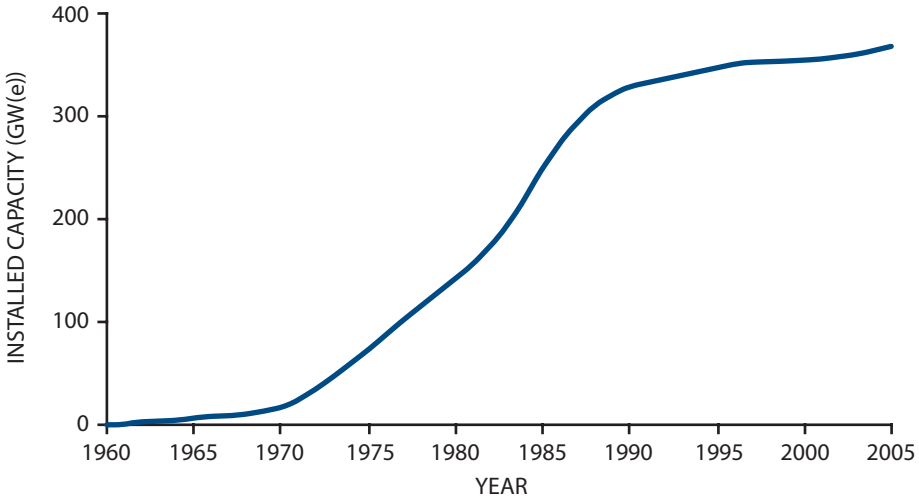
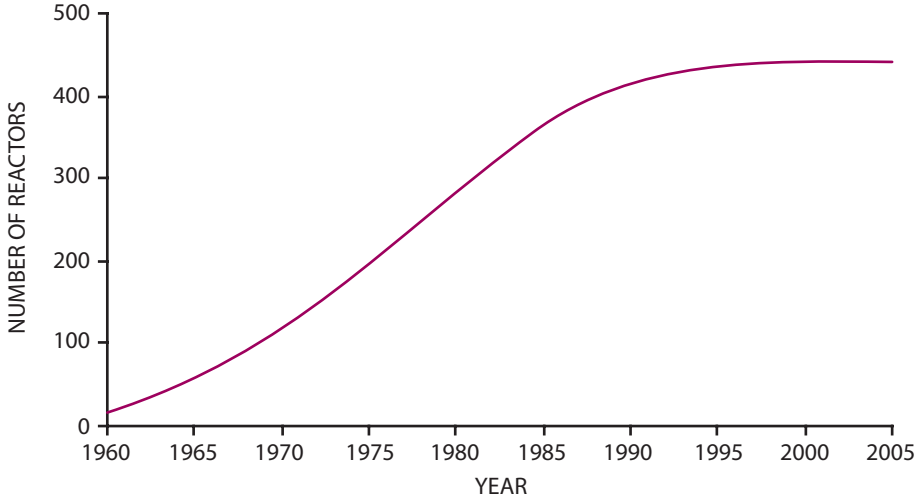
Figure XX. Trends in nuclear energy generation

(a) Total installed electrical energy capacity worldwide



(b) Total number of nuclear power reactors worldwide



(c) Average electrical energy capacity per reactor unit

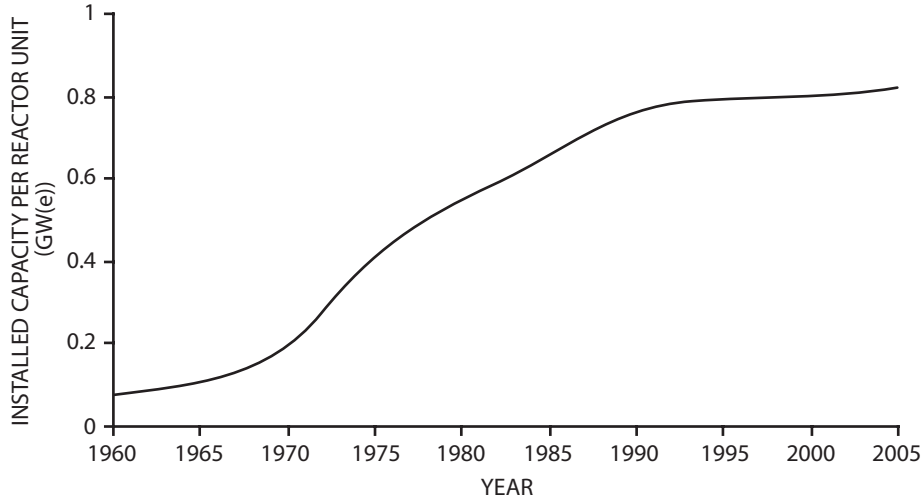


Figure XXI. Historical trends of energy generation by nuclear power reactors

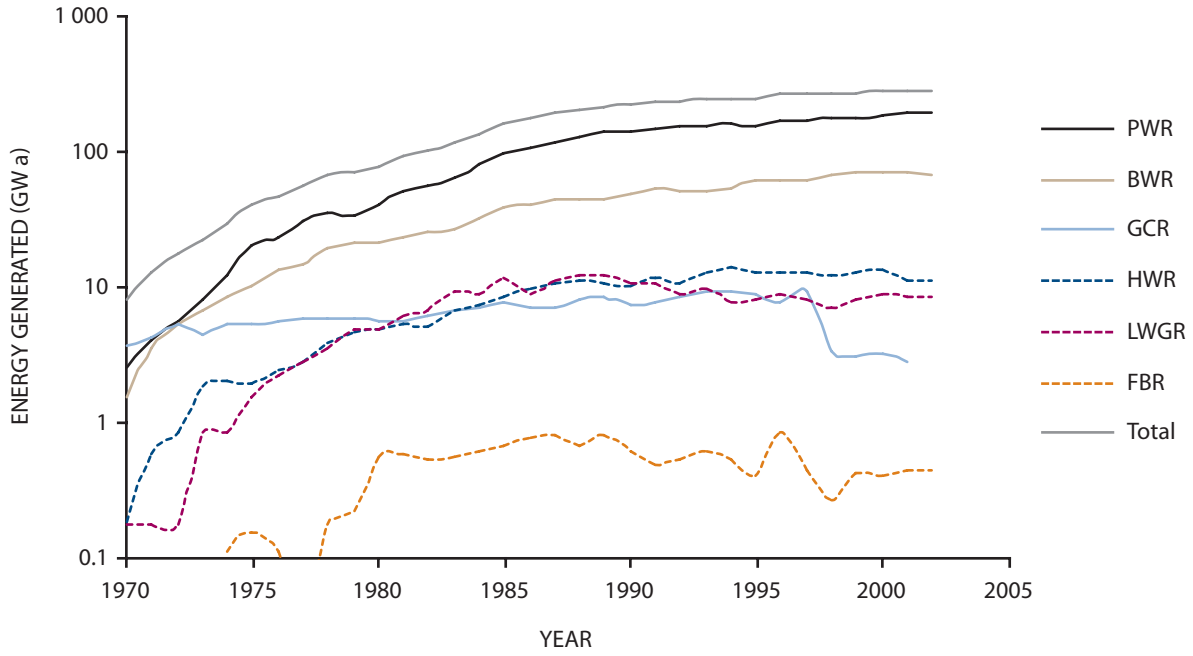


Figure XXII. Contribution of each type of reactor to the total nuclear energy generated in the periods 1970–1997 and 1998–2002

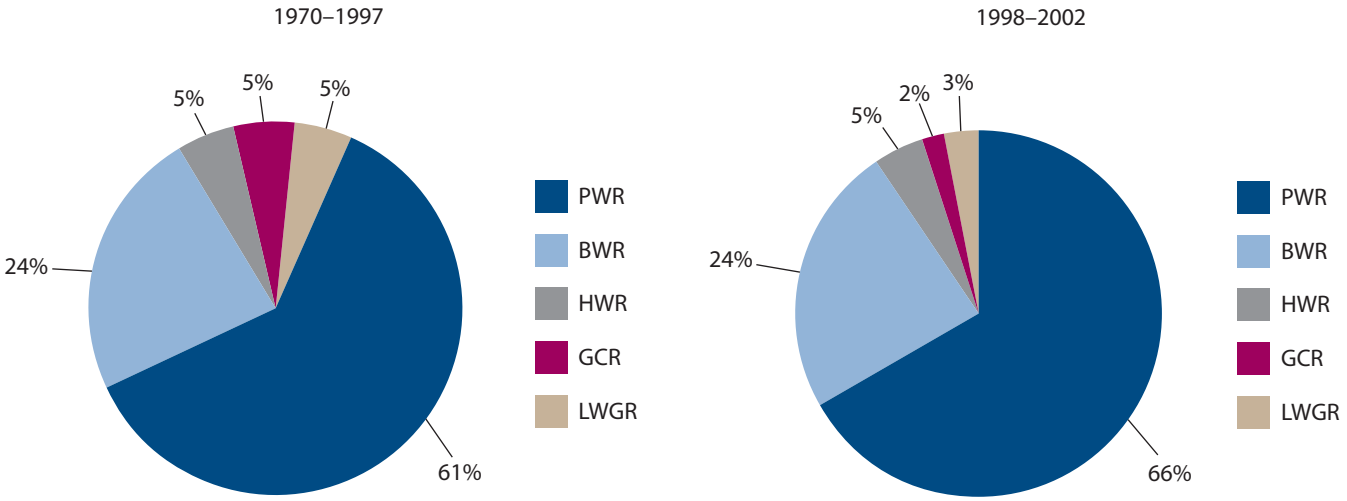


Figure XXIII. Normalized noble gas releases for different periods and types of reactor

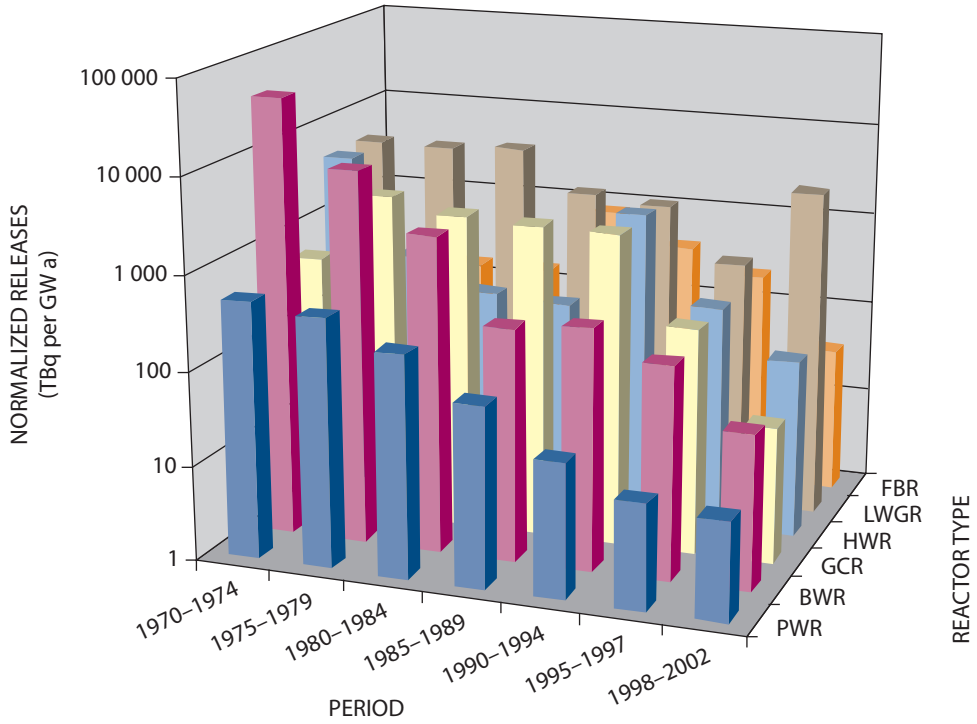


Figure XXIV. Number of nuclear fuel transports in Germany, including irradiated and non-irradiated fuel and waste, by road, rail, sea and air [B48]

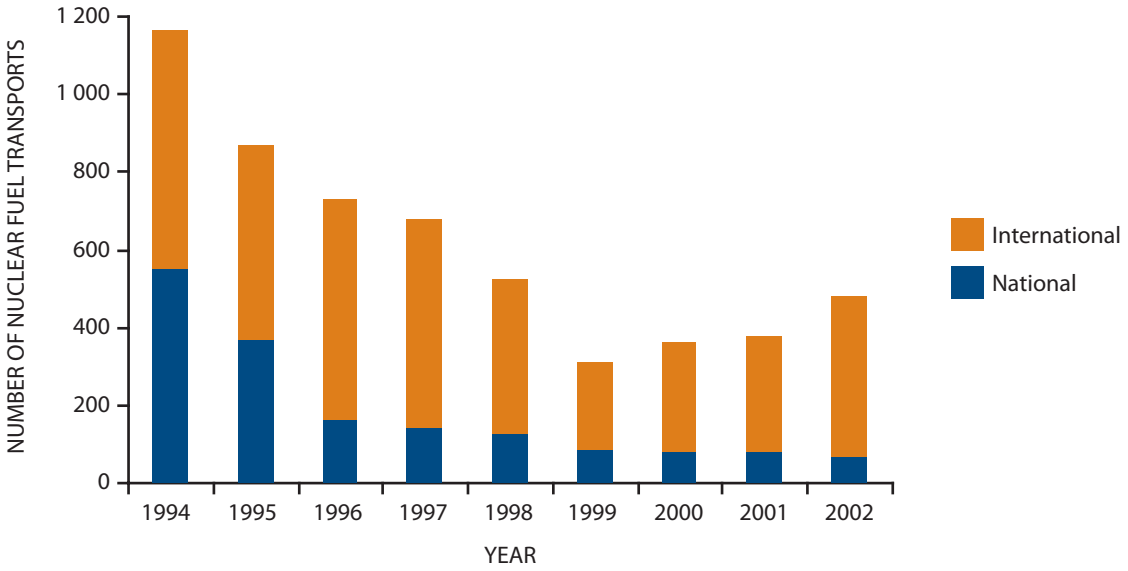


Figure XXV. Number of research reactors worldwide
Operational status (upper figure) and power range (lower figure)

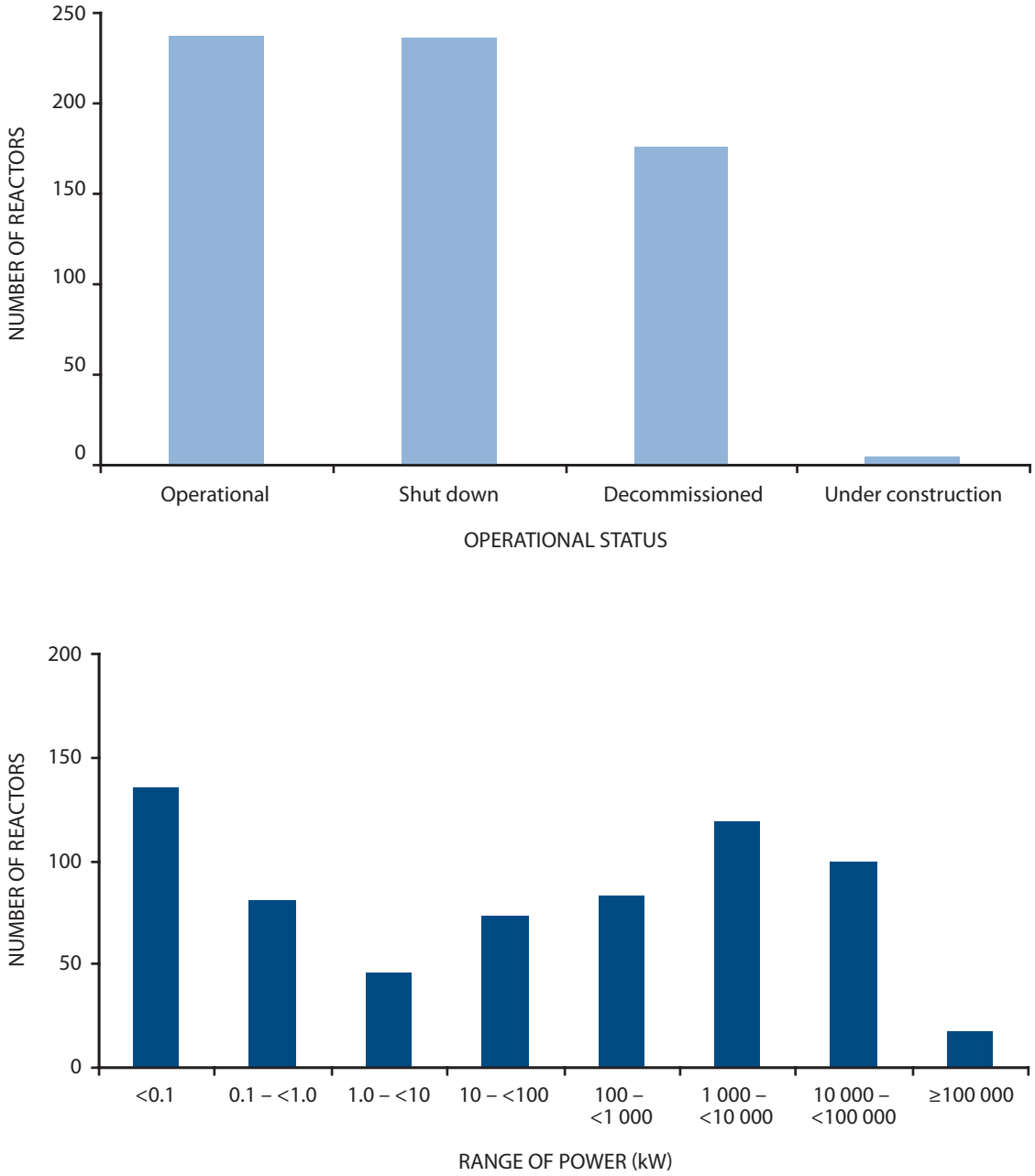
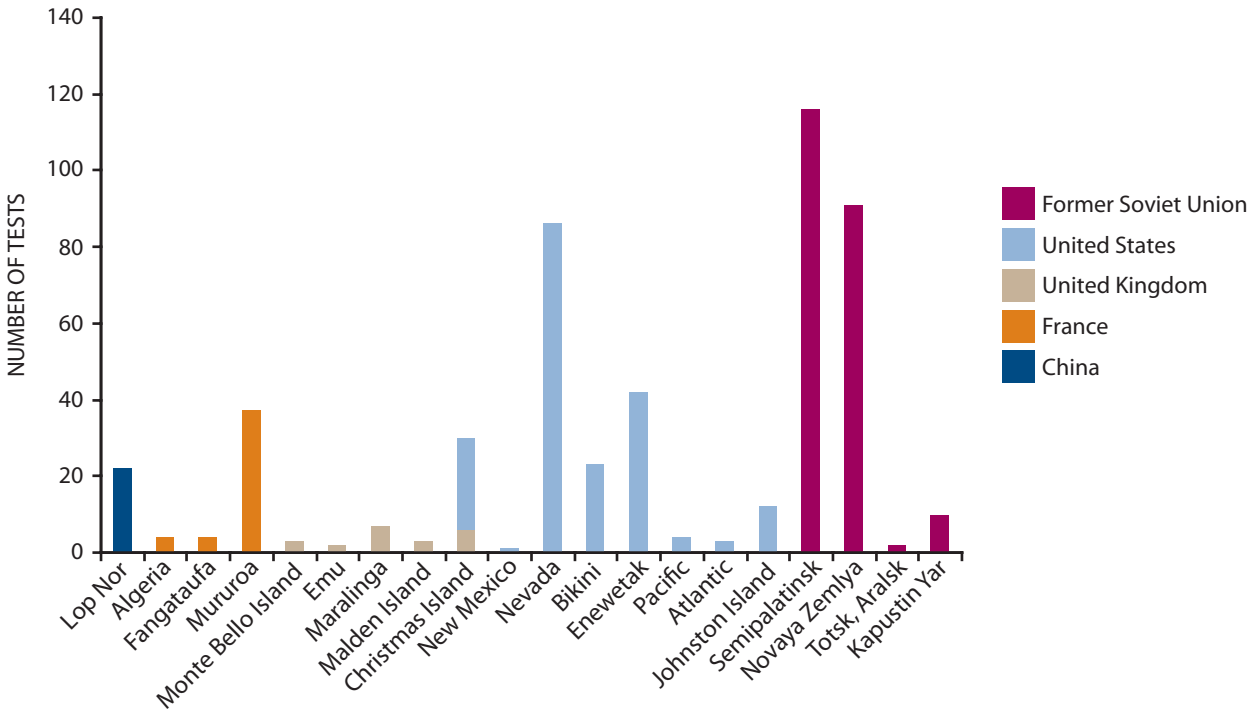


Figure XXVI. Number of tests and fission yields for different atmospheric layers for each nuclear test site

(a) Number of tests at each test site



(b) Fission yield at each test site

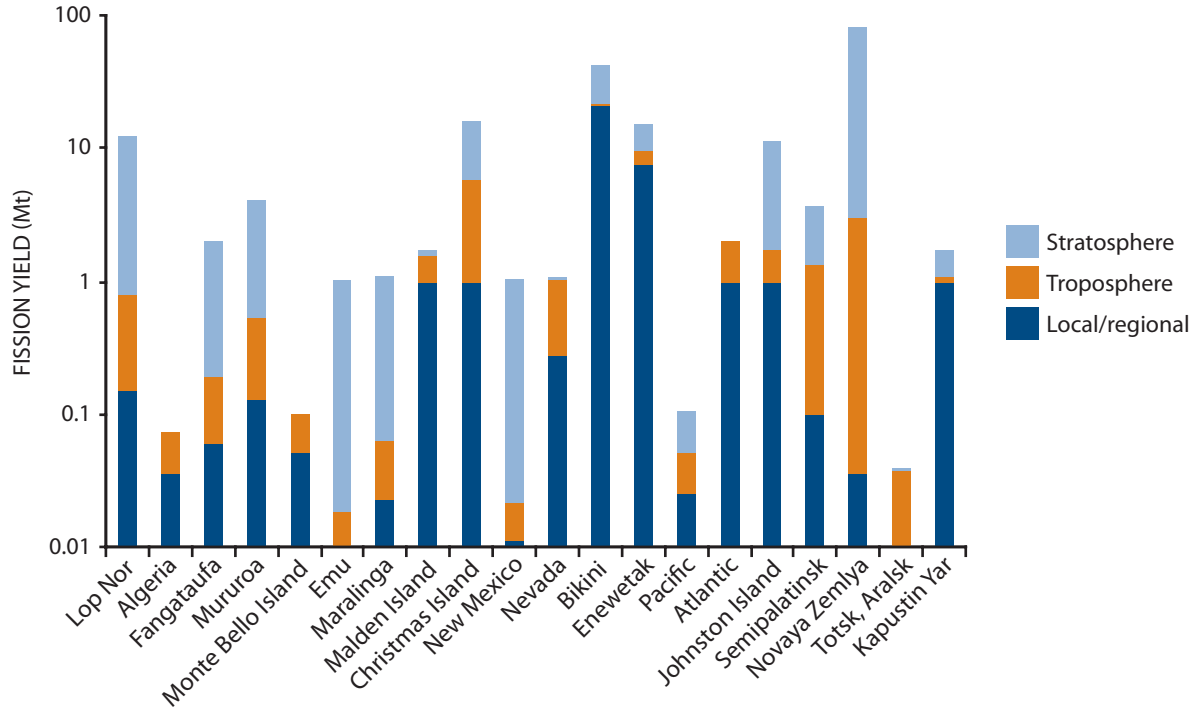


Figure XXVII. Worldwide average per caput effective doses from nuclear weapons tests

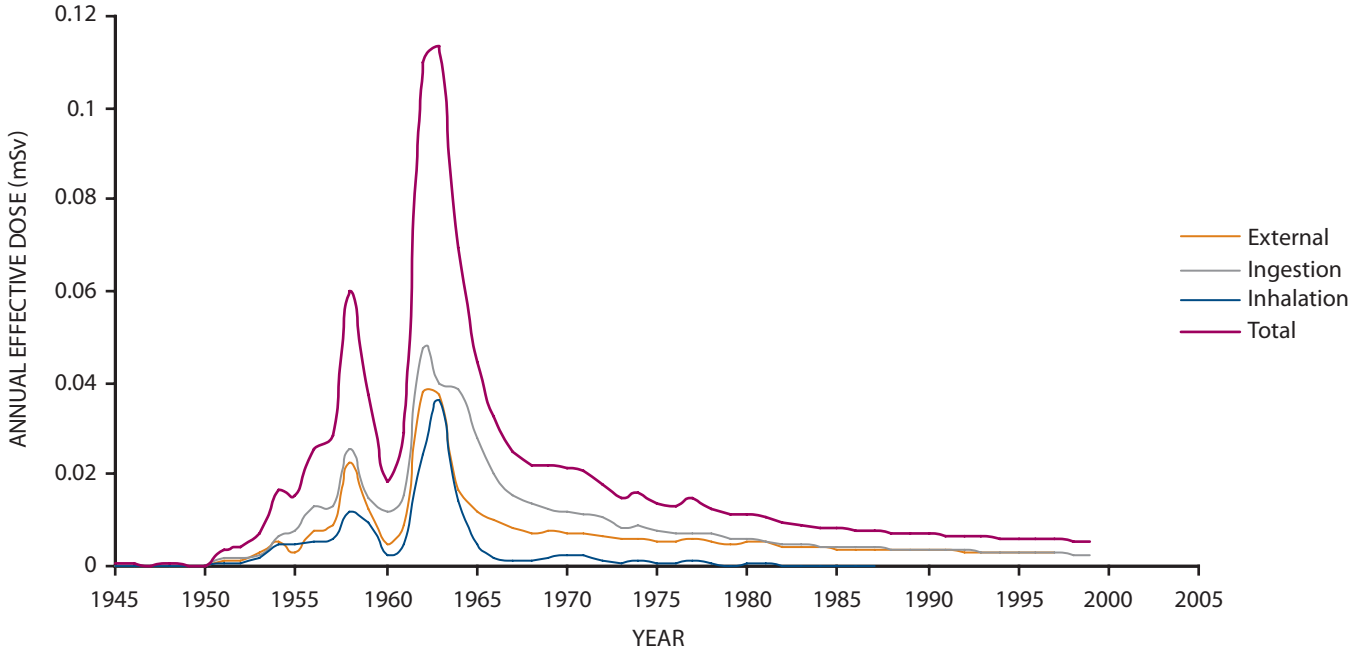
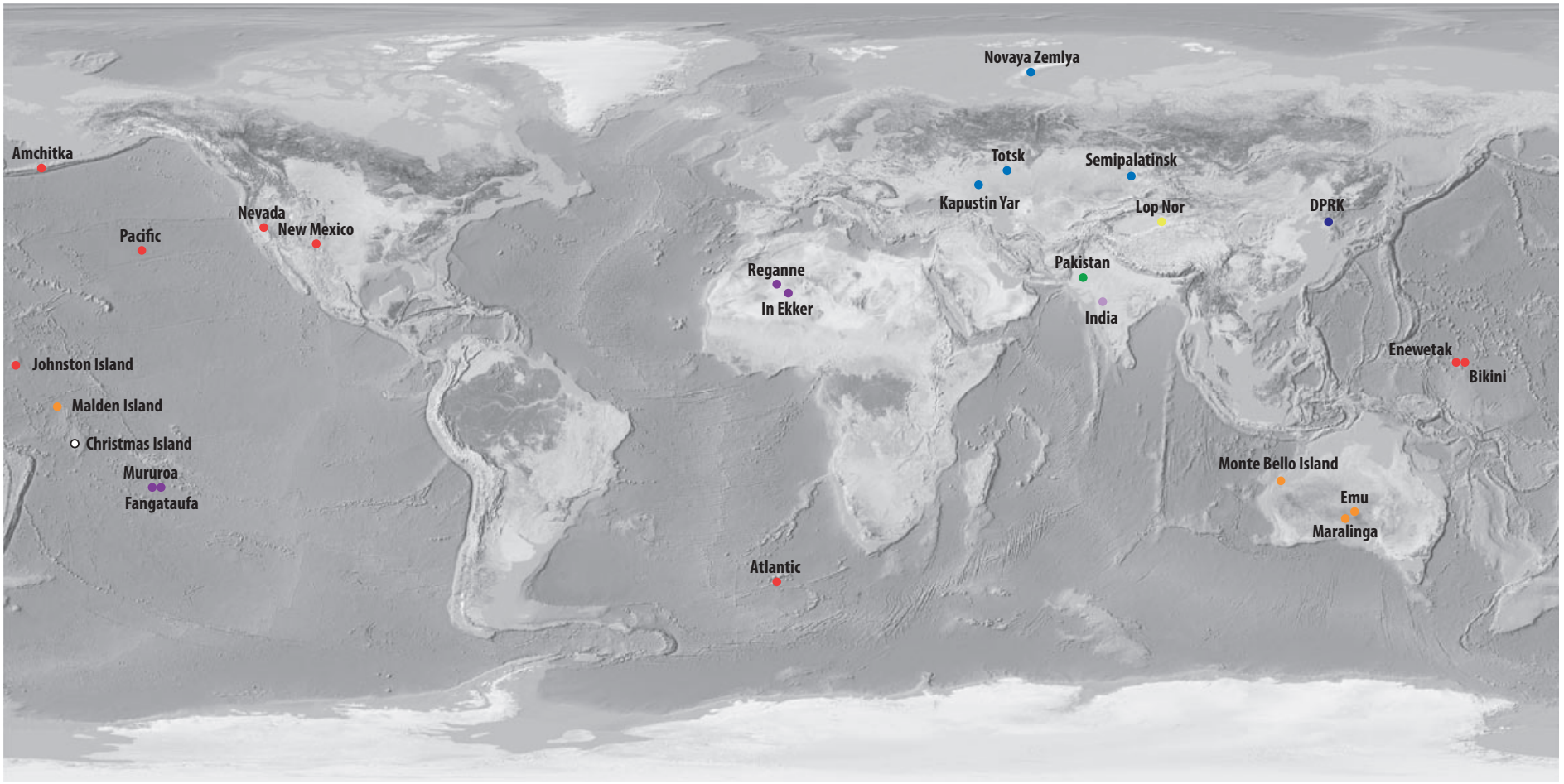


Figure XXVIII. Sites of nuclear weapons tests
Clean map from [C17]



The boundaries and names on these maps do not imply any official endorsement or acceptance by the United Nations

Figure XXIX. Number of nuclear tests performed by each country

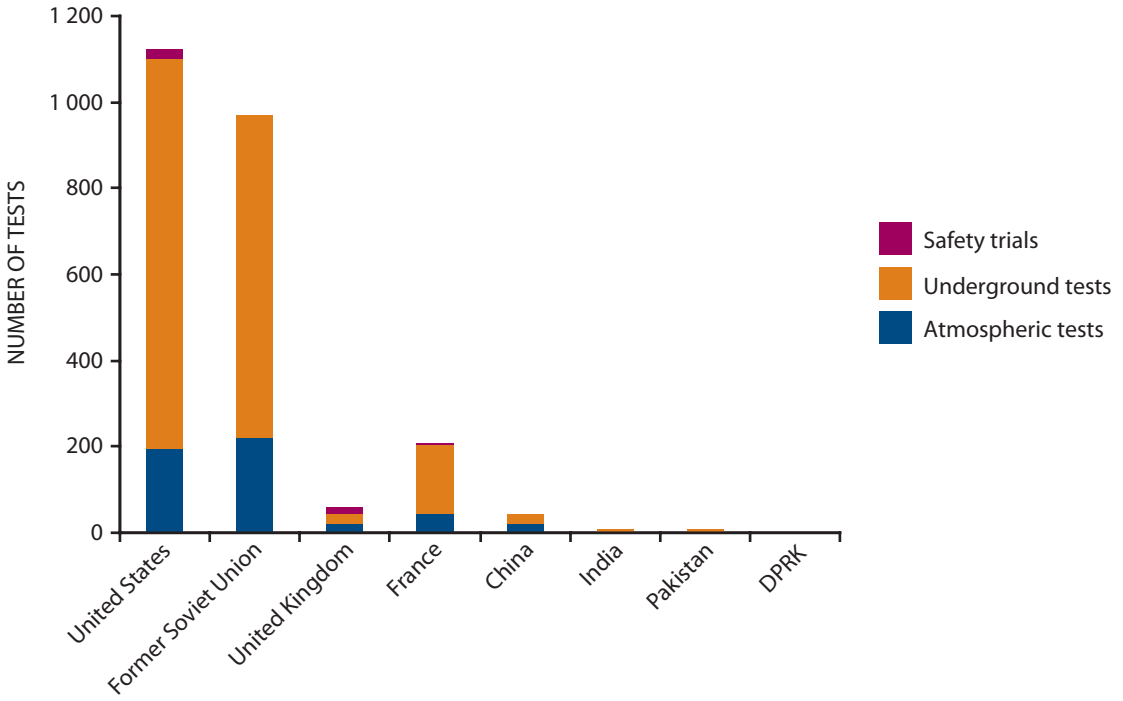


Figure XXX. Sites where radioactive waste has been dumped at sea [I11]

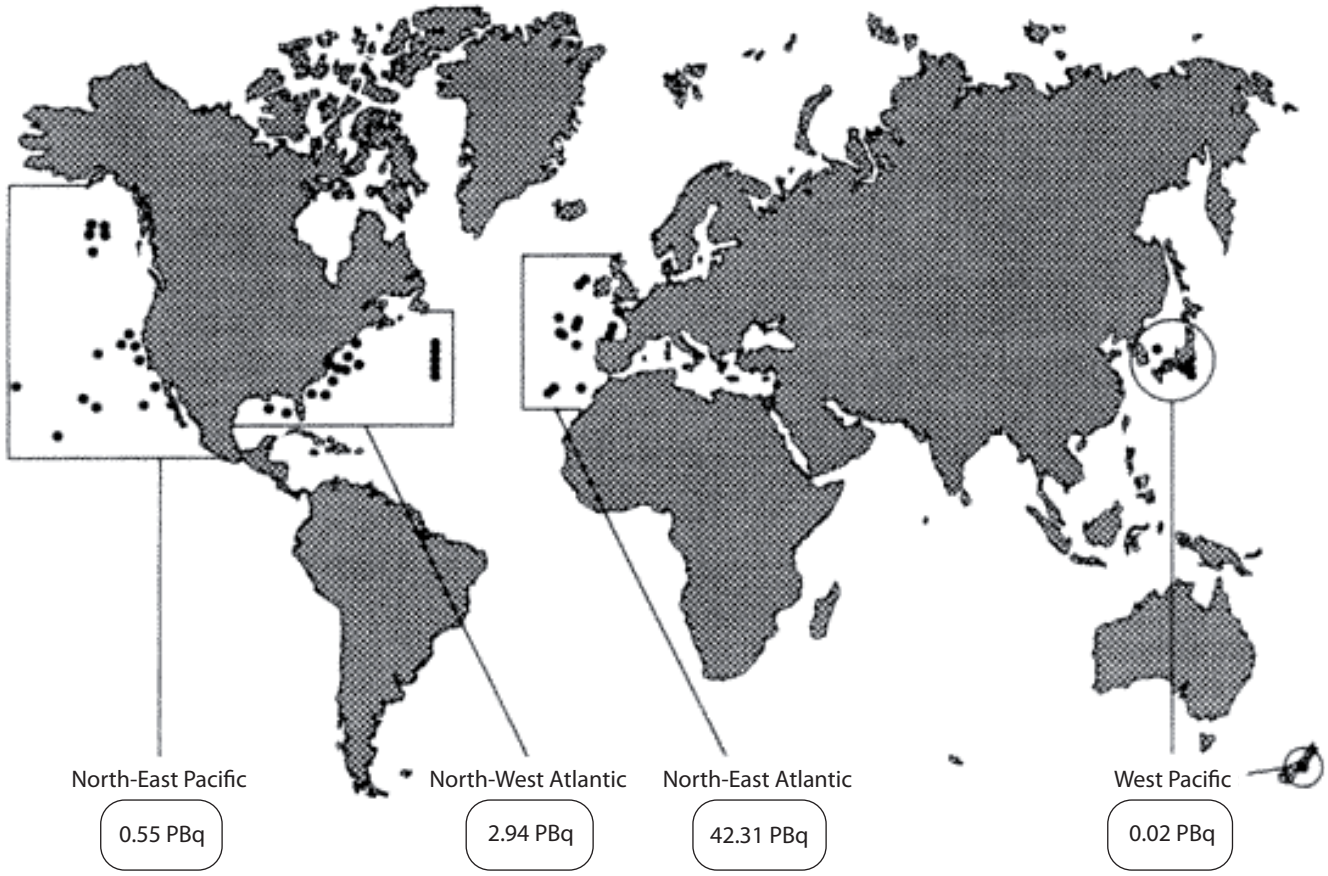


Figure XXXI. Locations where radioactive waste was dumped in the Kara Sea [I11]

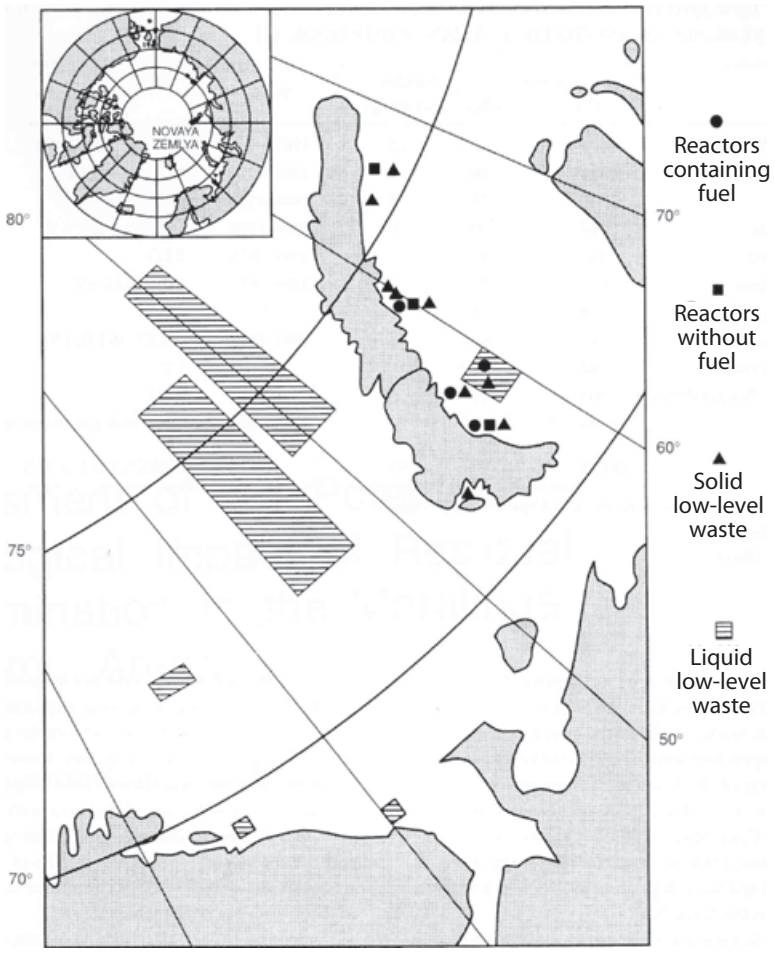


Figure XXXII. Spacecraft missions utilizing nuclear and/or radioactive material

RHU: radioisotope heating unit

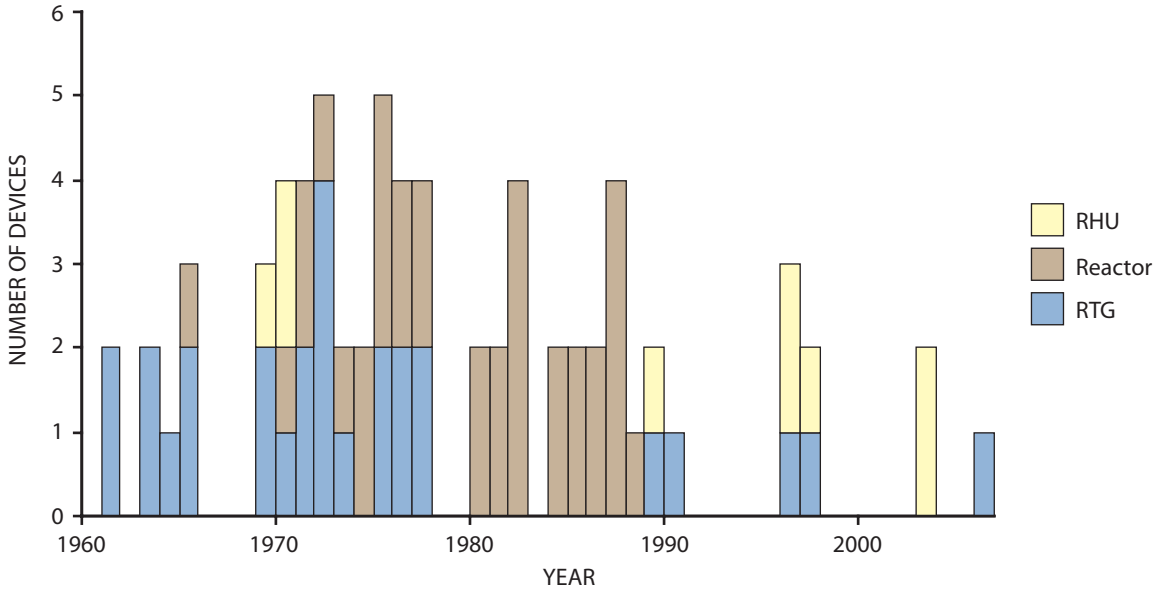


Figure XXXIII. Current status of devices utilizing nuclear and/or radioactive material in space: number of missions and number of devices

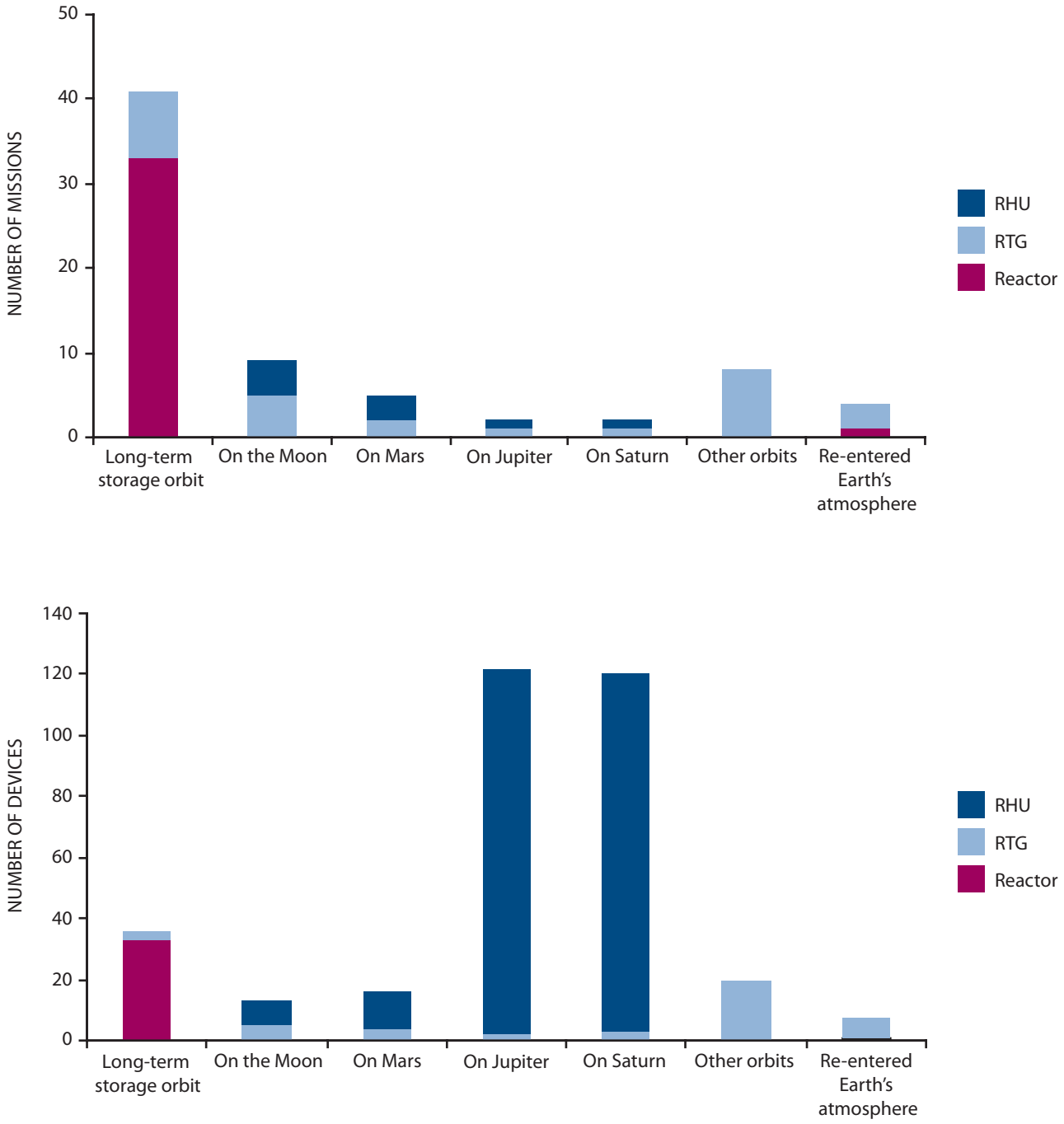
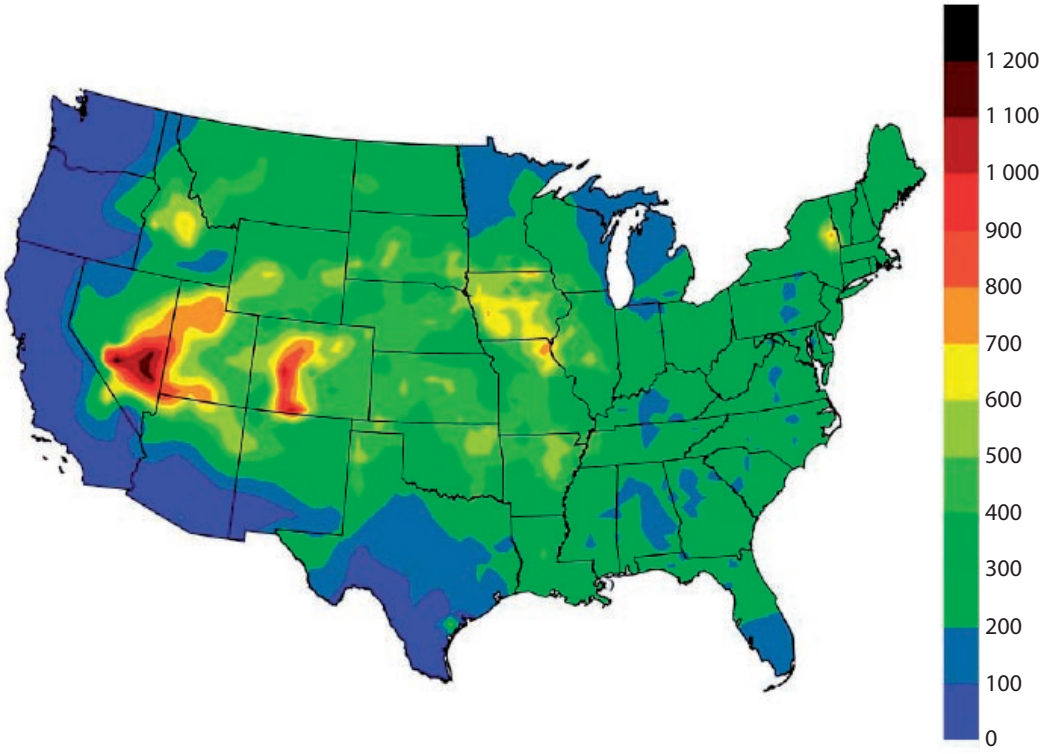


Figure XXXIV. Estimated ^{137}Cs deposition density (Bq/m^2) from NTS fallout (top figure) and from global fallout (bottom figure) across the continental United States [S23]



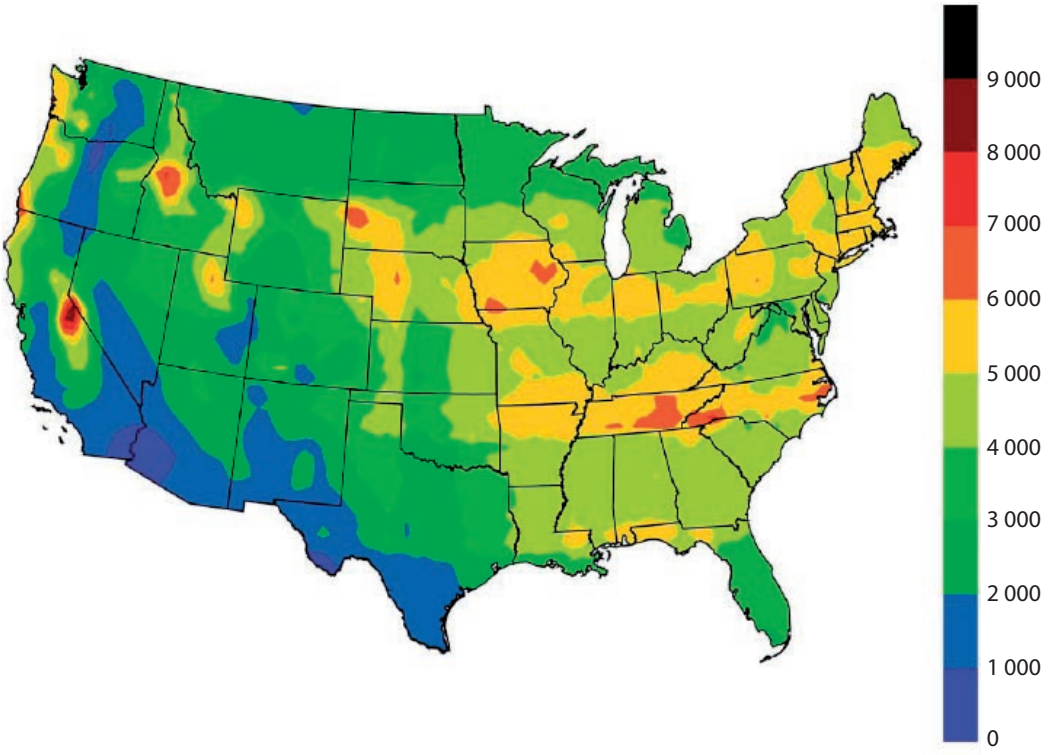


Figure XXXV. Sites of peaceful underground nuclear explosions in the former Soviet Union

Purposes of explosions: 1, obtaining seismic profiles; 2, creation of reservoirs in salt; 3, oil extraction; 4, creation of oil and gas inflow; 5, liquidation of oil wells; 6, burial of liquid toxic waste; 7, ore crushing; 8, creation of underground storage facilities in clay; 9, ground excavation; 10, ground loosening [V1]

Figure XXXVI. Estimated contributions to public exposure from different sources for different countries, and UNSCEAR estimates of worldwide average exposures

Figures for the United States from references [M23, N8], for Germany from [B49], for the United Kingdom from [W6]. Different distributions can be expected for other countries, as all countries considered here have a high level of development. For Germany, "Other" includes exposure due to fallout resulting from nuclear tests, to the Chernobyl accident and to releases from nuclear power plants

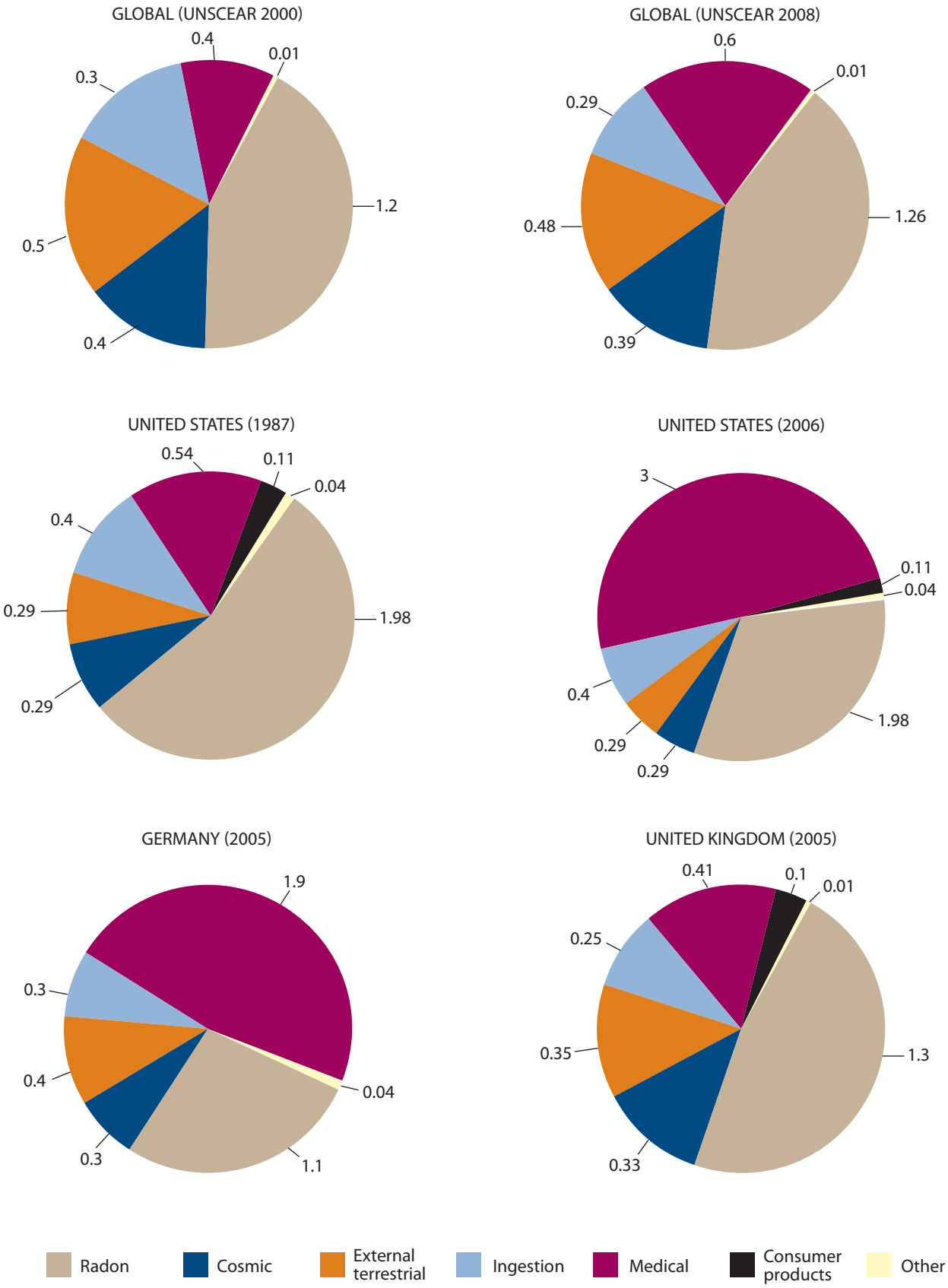
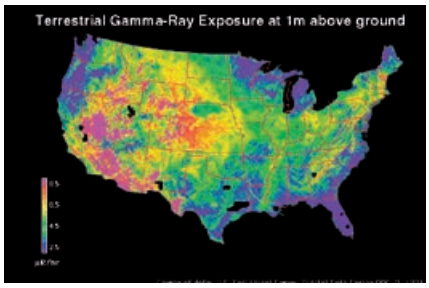


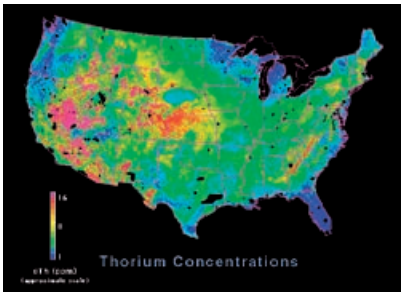
Figure XXXVII. Example of different dose distributions affecting public exposure in the United States

(a) Altitude and latitude effects on cosmic radiation dose [U26]; *(b)* external gamma exposure [U28]; *(c, d, e)* distributions of the natural terrestrial radionuclides Th, U and K, which contribute to ingestion and inhalation doses [U28]; *(f)* indoor radon, main contributor to public exposure from natural sources via inhalation [U28]; *(g)* doses from fallout resulting from nuclear tests [N6]; *(h)* location of nuclear power plants [U39]. All these source distributions would be combined with *(i)*, population distribution [U28]

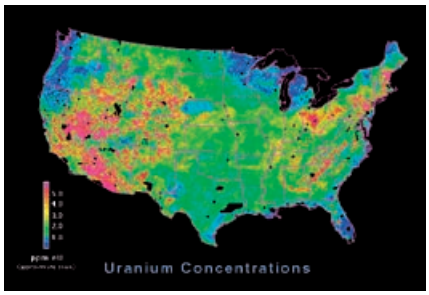
(a)



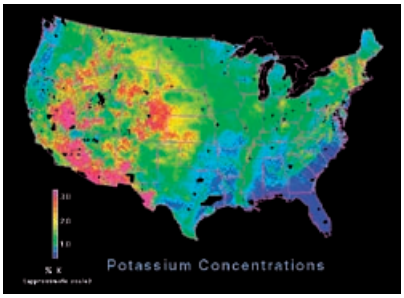
(b)



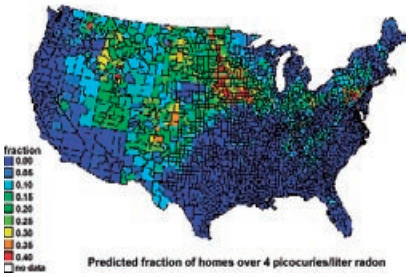
(c)



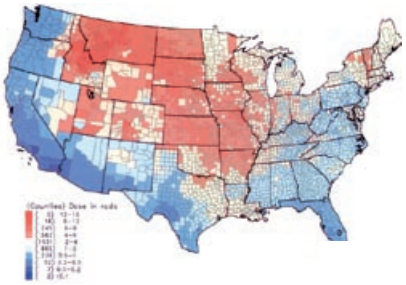
(d)



(e)

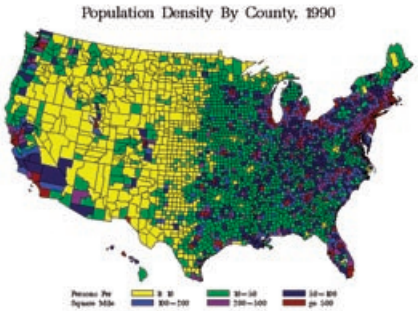


(f)



(g)

(h)



(i)

Figure XXXVIII. Worldwide trends in occupational exposure due to uranium mining

Average annual numbers of monitored workers, and collective effective doses and effective doses to monitored workers

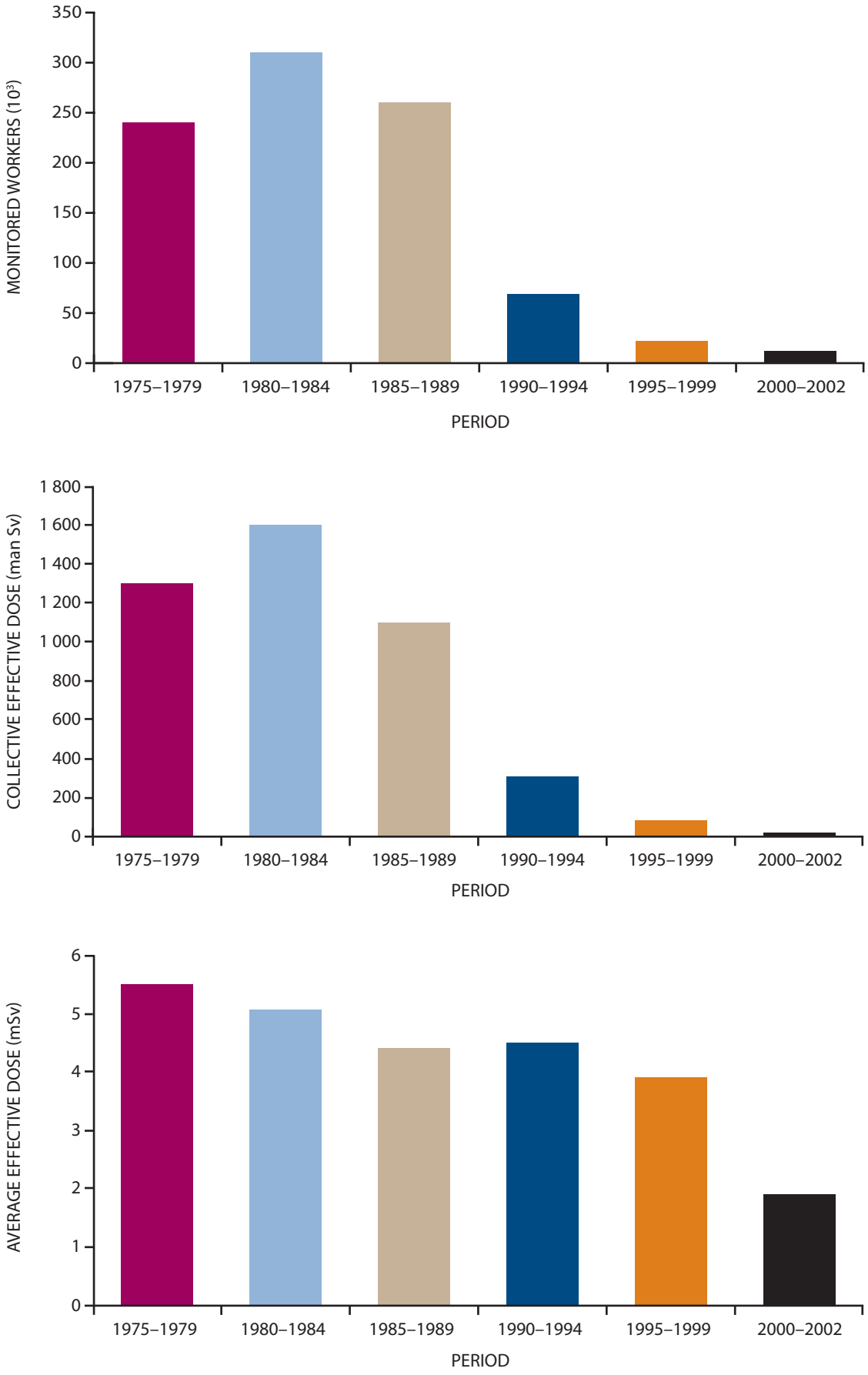


Figure XXXIX. Worldwide trends in occupational exposure due to uranium milling

Average annual numbers of monitored workers, and collective effective doses and effective doses to monitored workers

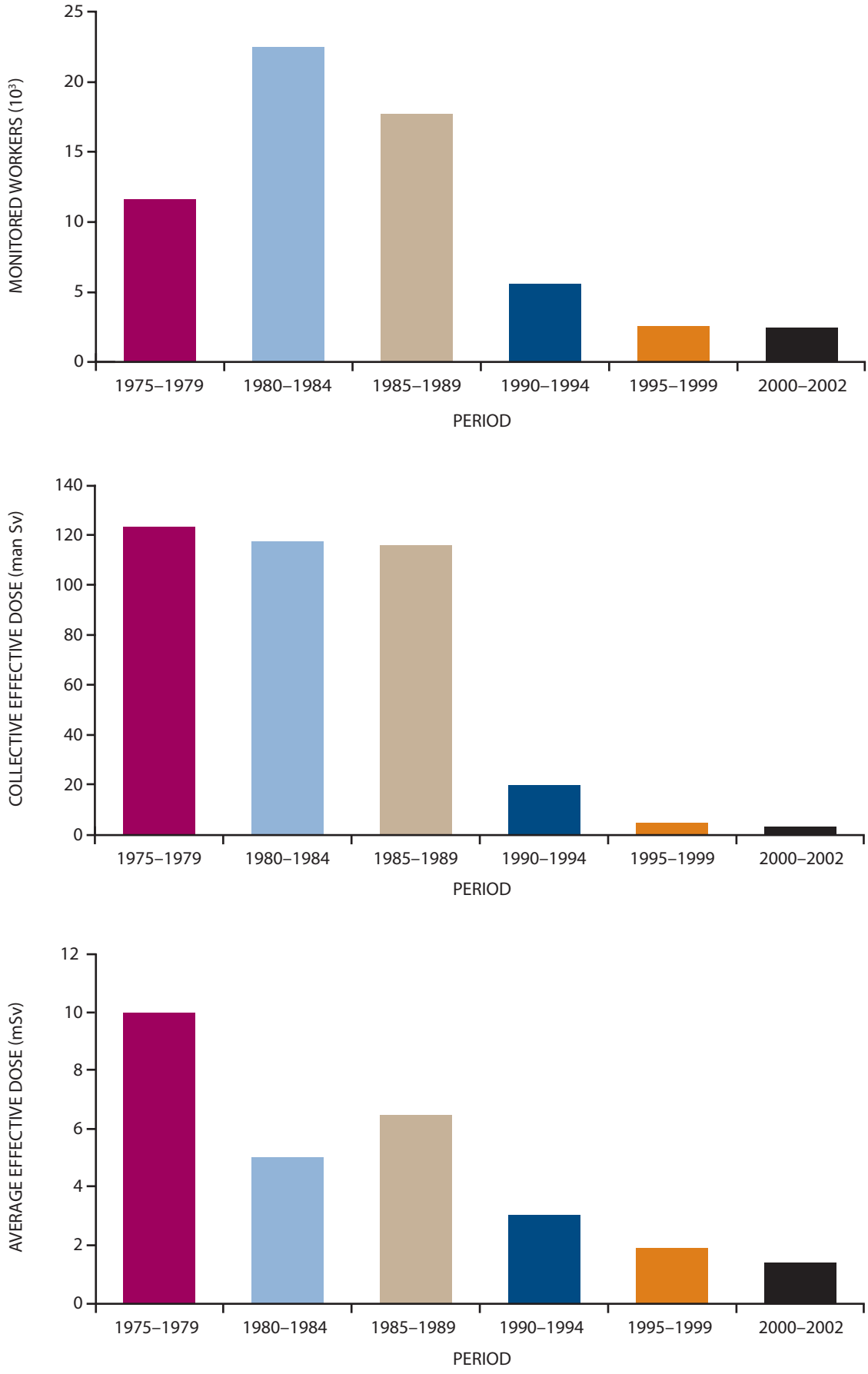


Figure XL. Worldwide trends in occupational exposure due to uranium enrichment and conversion
Average annual numbers of monitored workers, and collective effective doses and effective doses to monitored workers

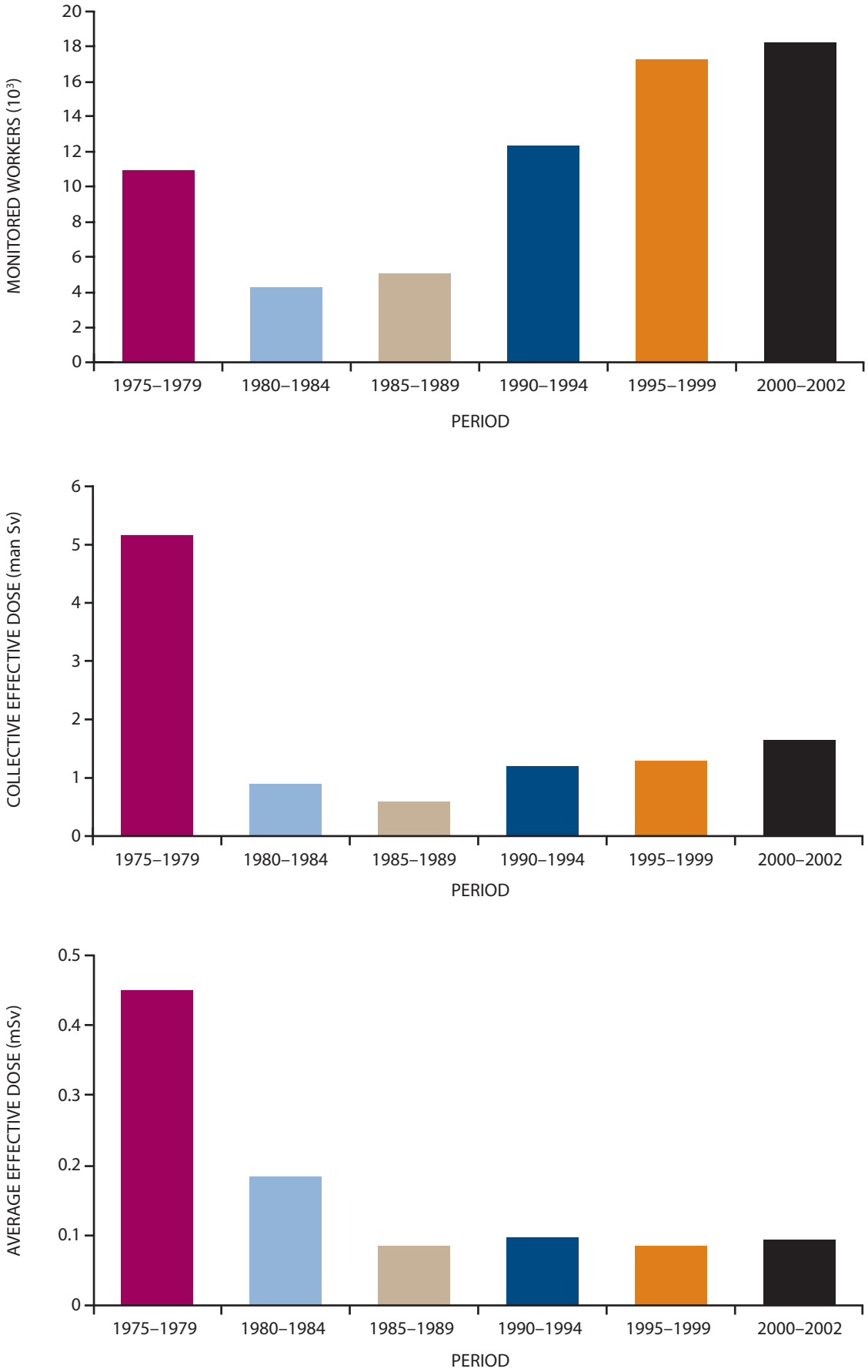


Figure XLI. Worldwide trends in occupational exposure due to nuclear fuel production

Average annual numbers of monitored workers, and collective effective doses and effective doses to monitored workers

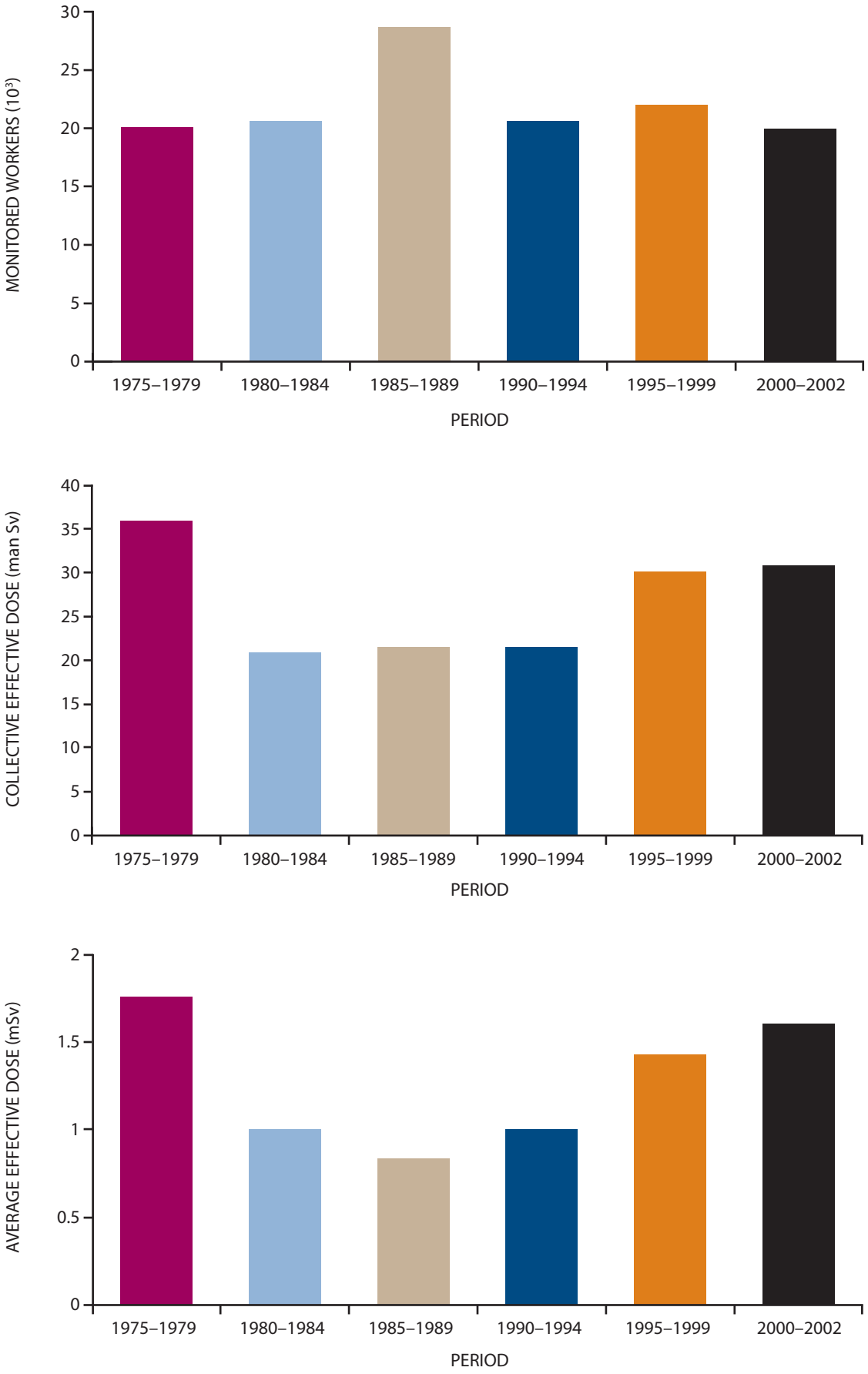


Figure XLII. Worldwide trends in occupational exposure due to reactor operation
Average annual numbers of monitored workers, and collective effective doses and effective doses to monitored workers

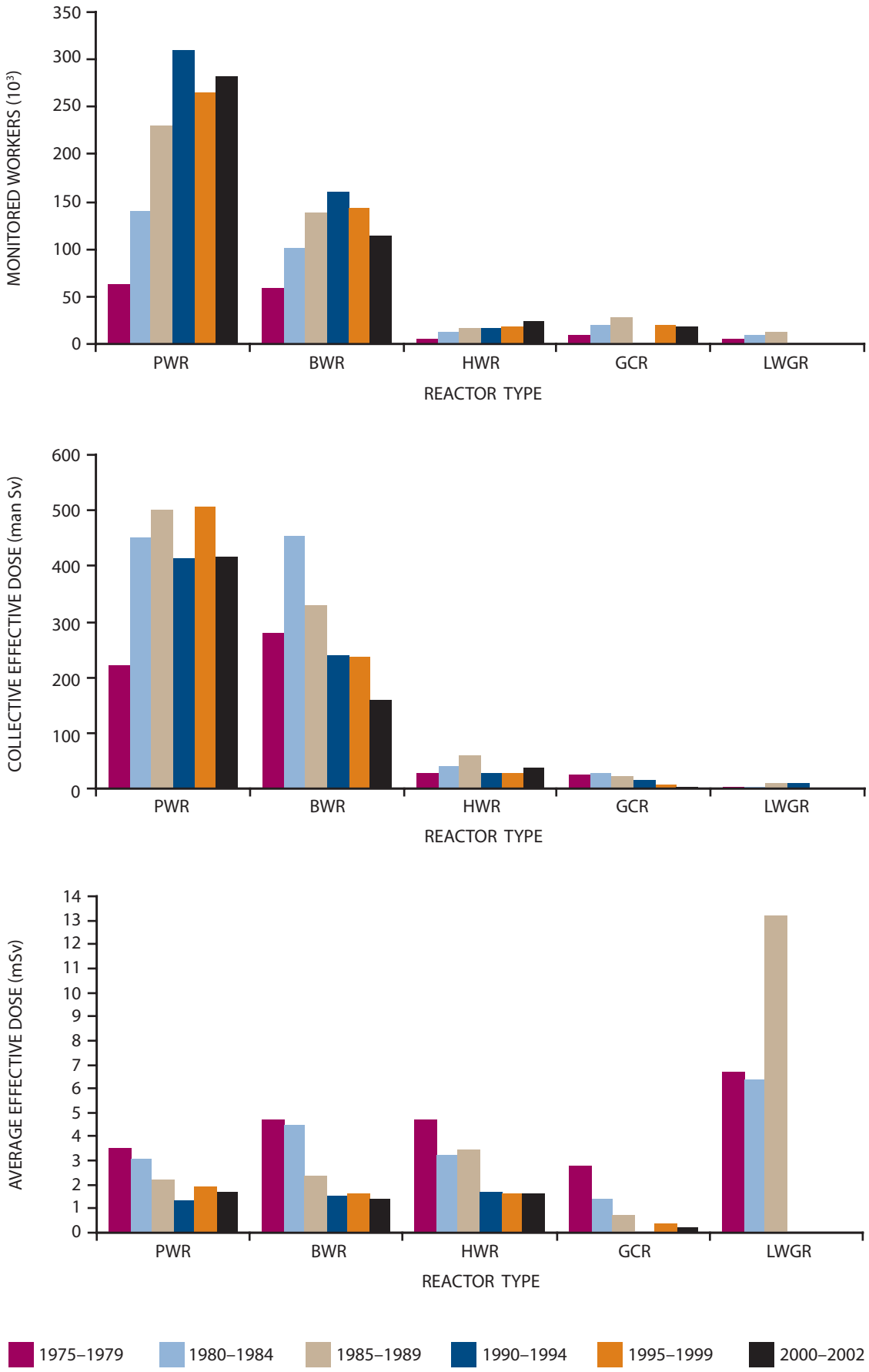


Figure XLIII. Worldwide trends in collective effective dose due to reactor operation, and in normalized collective effective dose per reactor and per unit electrical energy

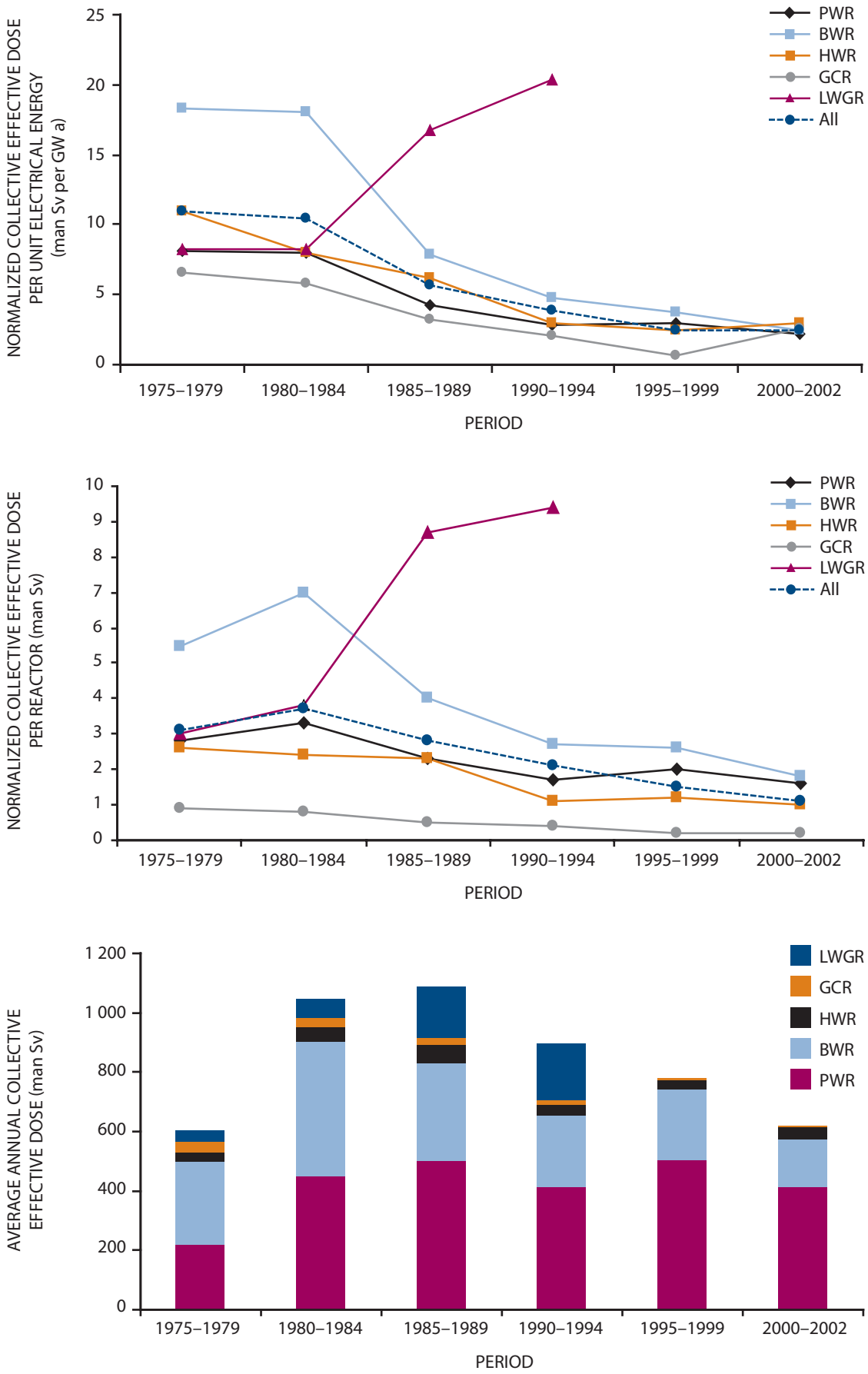


Figure XLIV. Worldwide trends in occupational exposure due to fuel reprocessing

Average annual numbers of monitored workers, and collective effective doses and effective doses to monitored workers

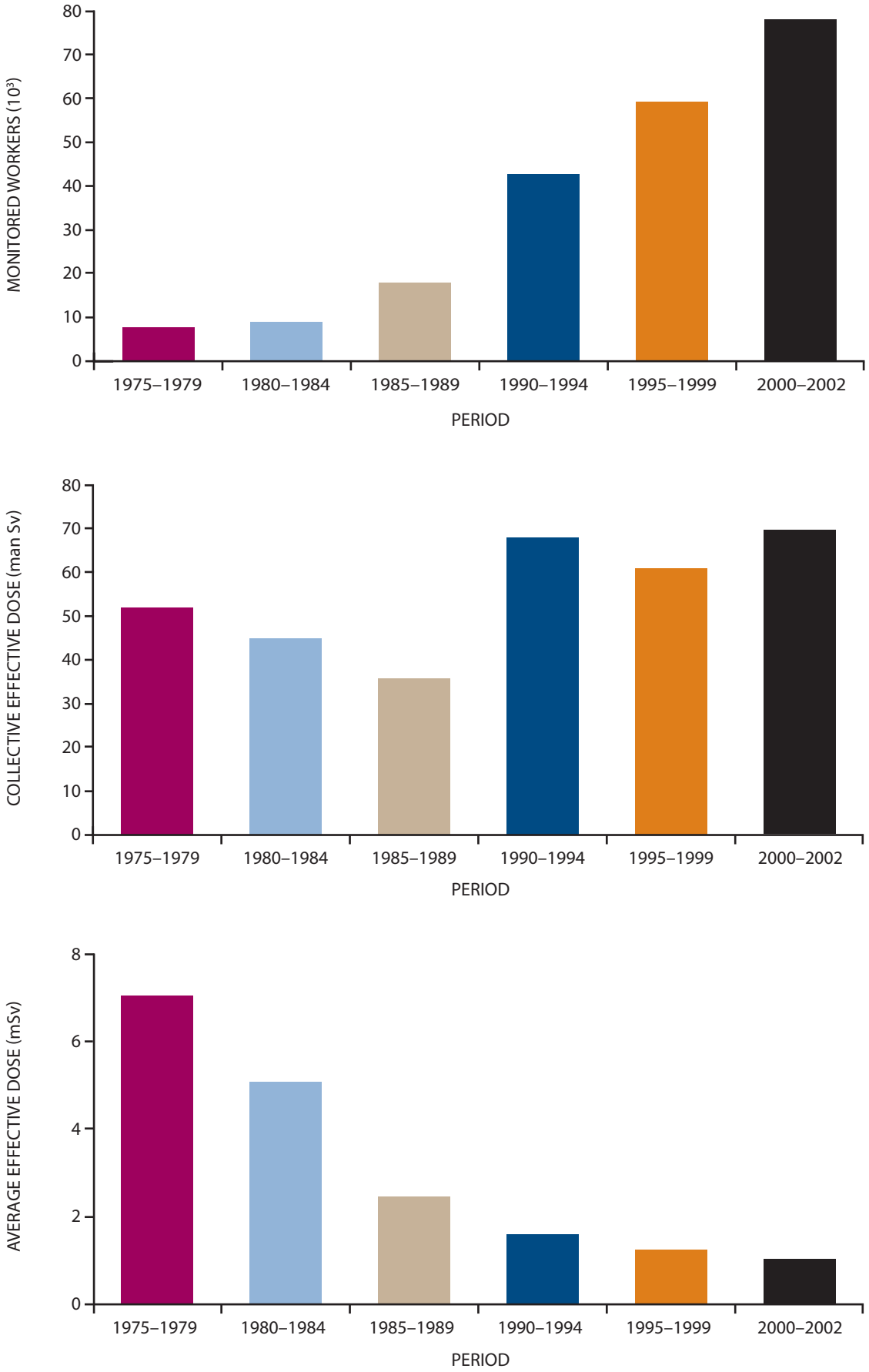


Figure XLV. Worldwide trends in occupational exposure due to research related to the nuclear fuel cycle
Average annual numbers of monitored workers, and collective effective doses and effective doses to monitored workers

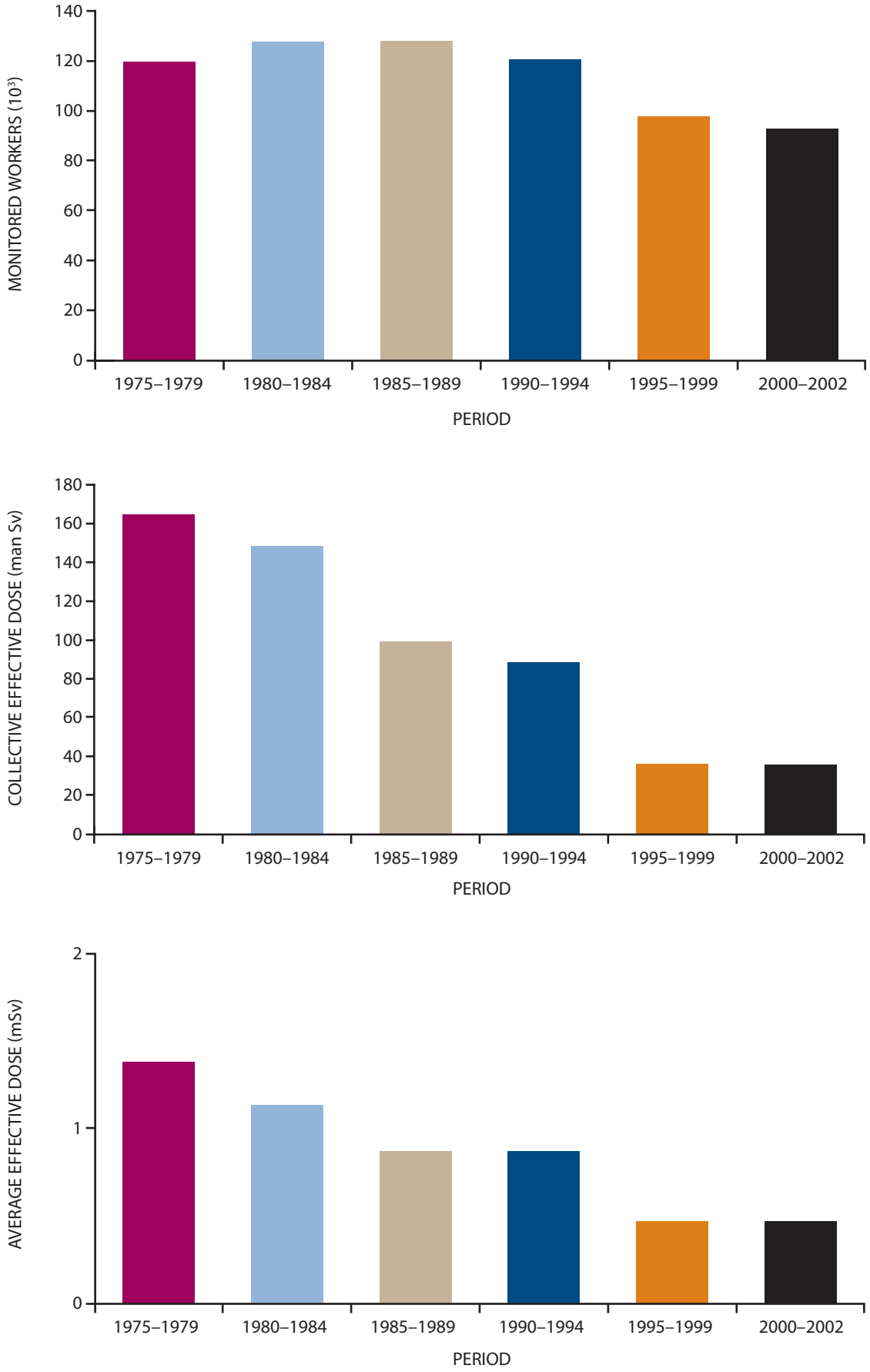


Figure XLVI. Worldwide trends in the number of monitored workers, and in collective effective doses and effective doses to workers for different practices of the nuclear fuel cycle

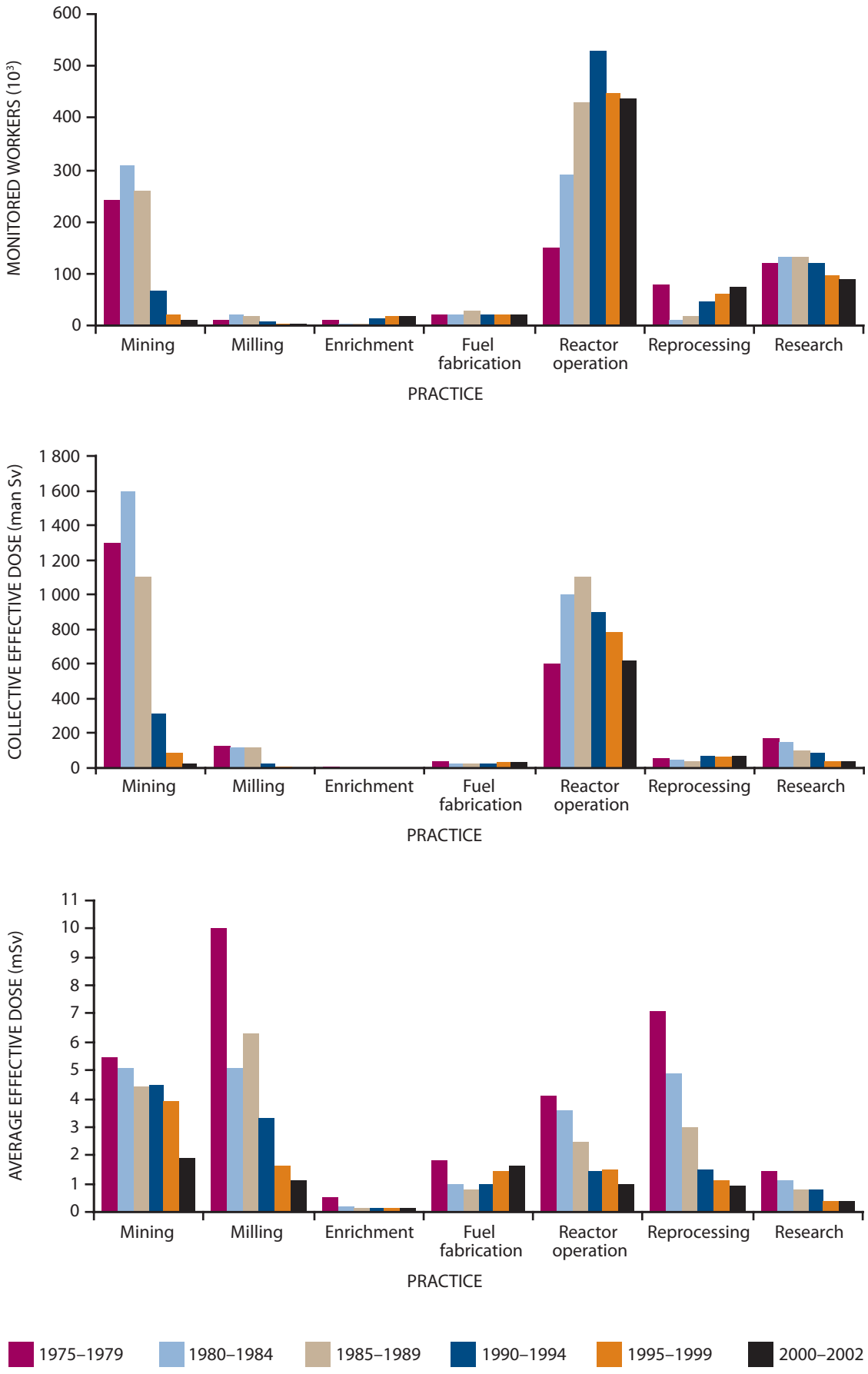


Figure XLVII. Worldwide trends in the number of monitored workers, and in collective effective doses and effective doses to workers in the nuclear fuel cycle

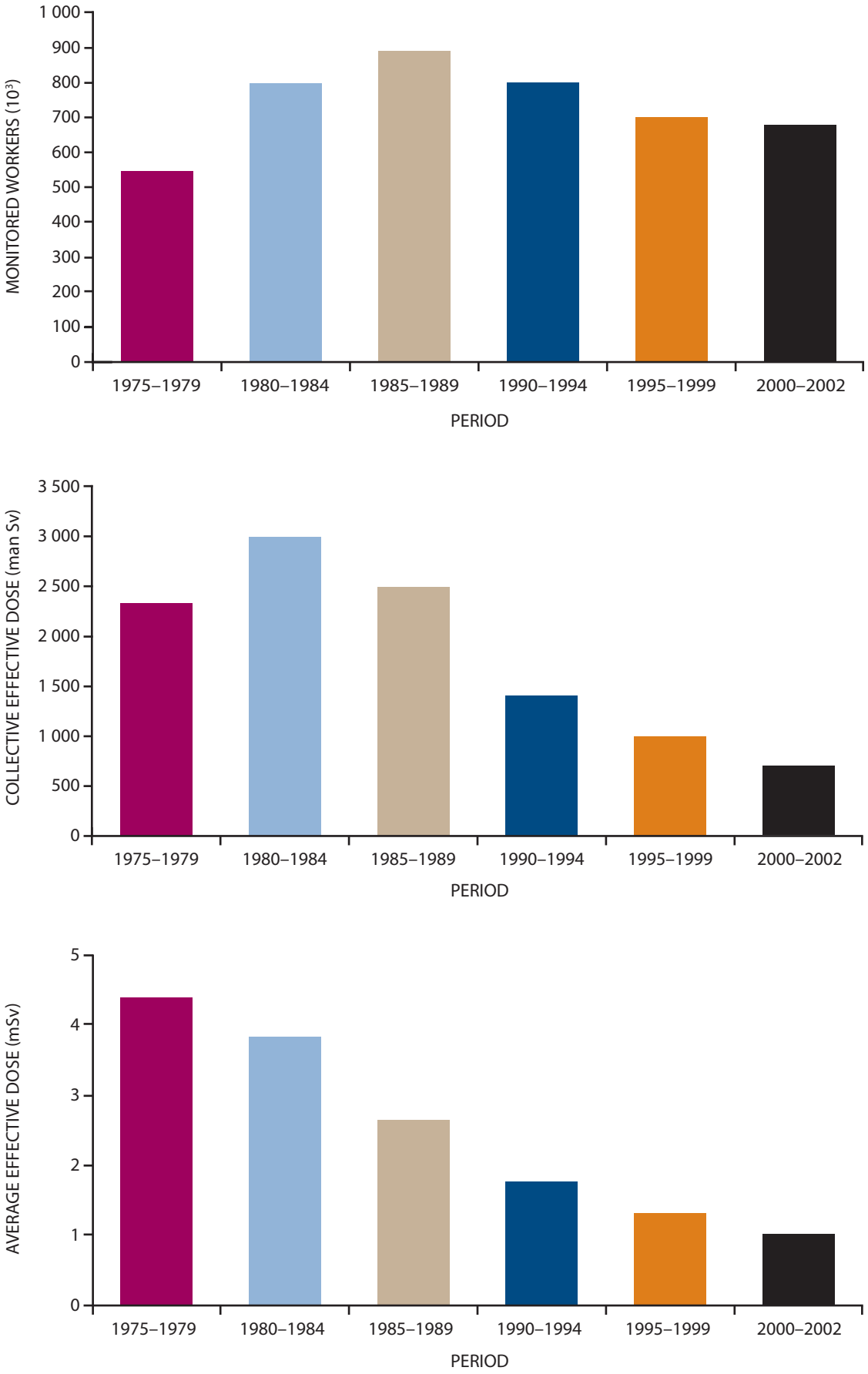
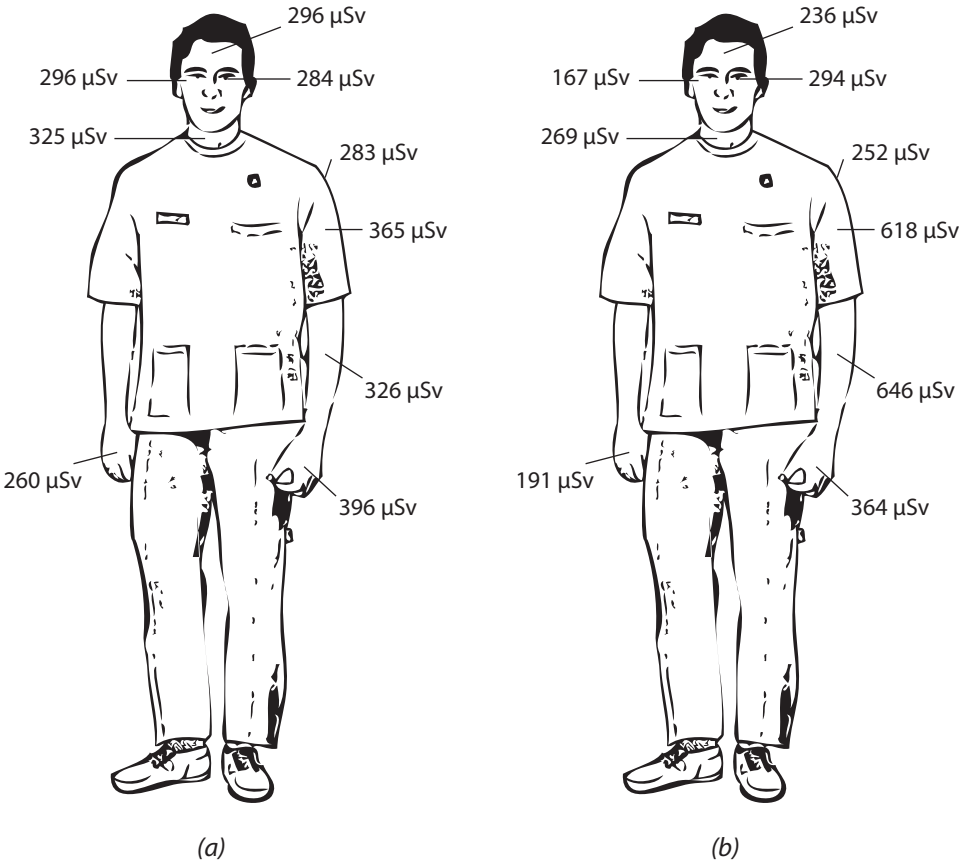


Figure XLVIII. Dose levels for *(a)* interventional radiologist and *(b)* interventional cardiologist
Average values of 83 procedures performed by ten specialists in six laboratories [V7]



(a) *(b)*

Figure XLIX. Worldwide trends in occupational exposure due to diagnostic radiology
Average annual numbers of monitored workers, and collective effective doses and effective doses to monitored workers

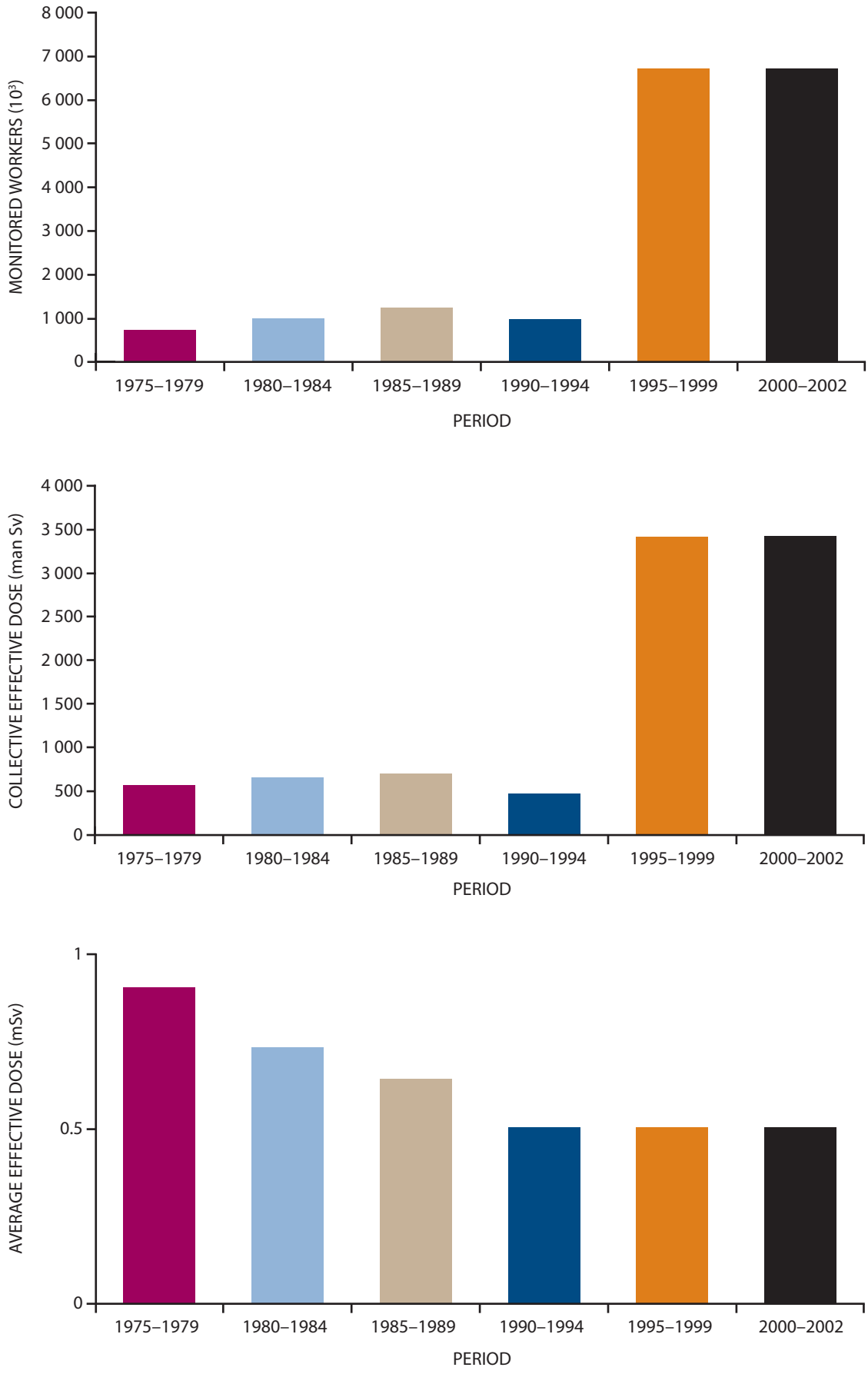
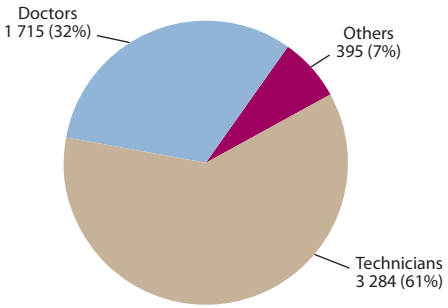


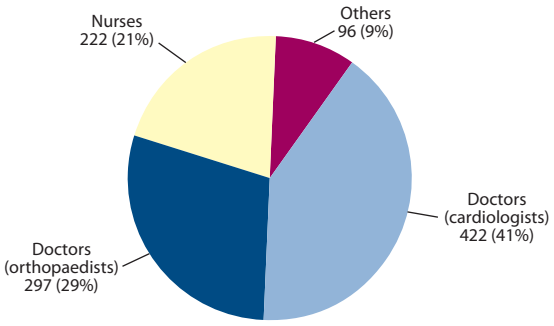
Figure L. Occupational exposures due to diagnostic radiology in Greece for various job categories

CONVENTIONAL PROCEDURES

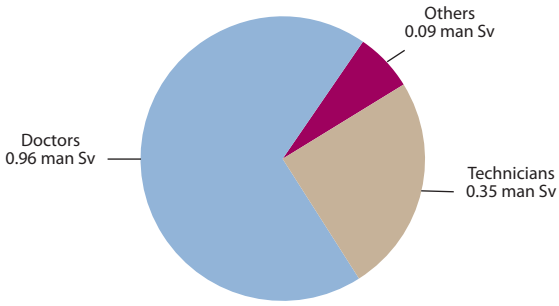
INTERVENTIONAL PROCEDURES

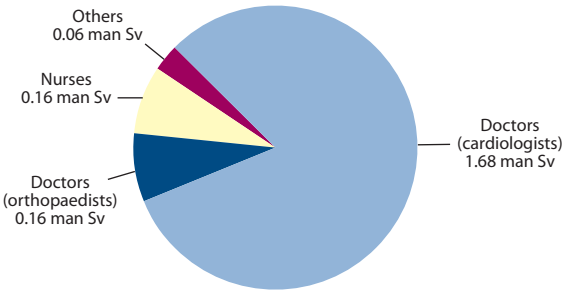
(a) Numbers of monitored workers for conventional and interventional procedures



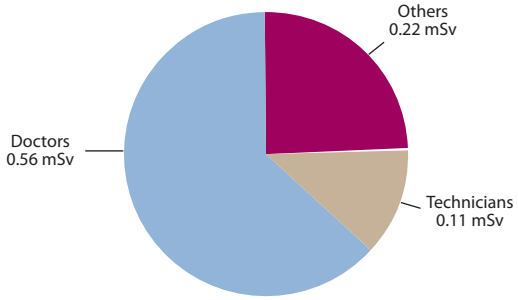


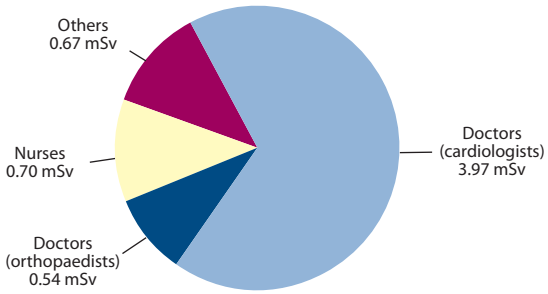
(b) Collective effective doses for conventional and interventional procedures



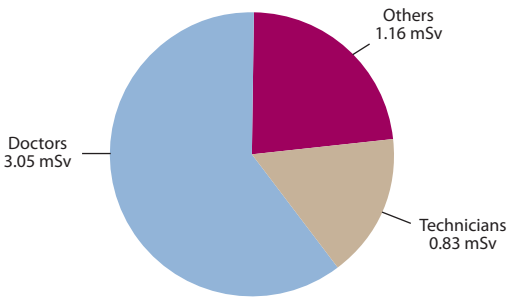


(c) Average effective doses to monitored workers





(d) Average effective doses to measurably exposed workers



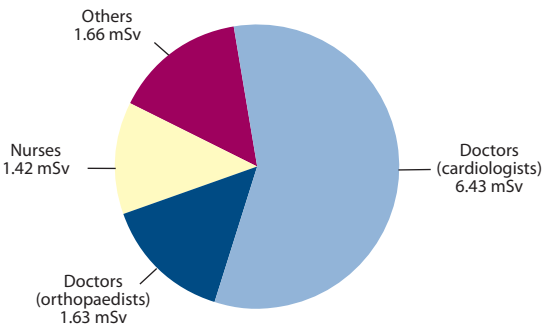


Figure LI. Worldwide trends in occupational exposure due to dental practice

Average annual numbers of monitored workers, and collective effective doses and effective doses to monitored workers

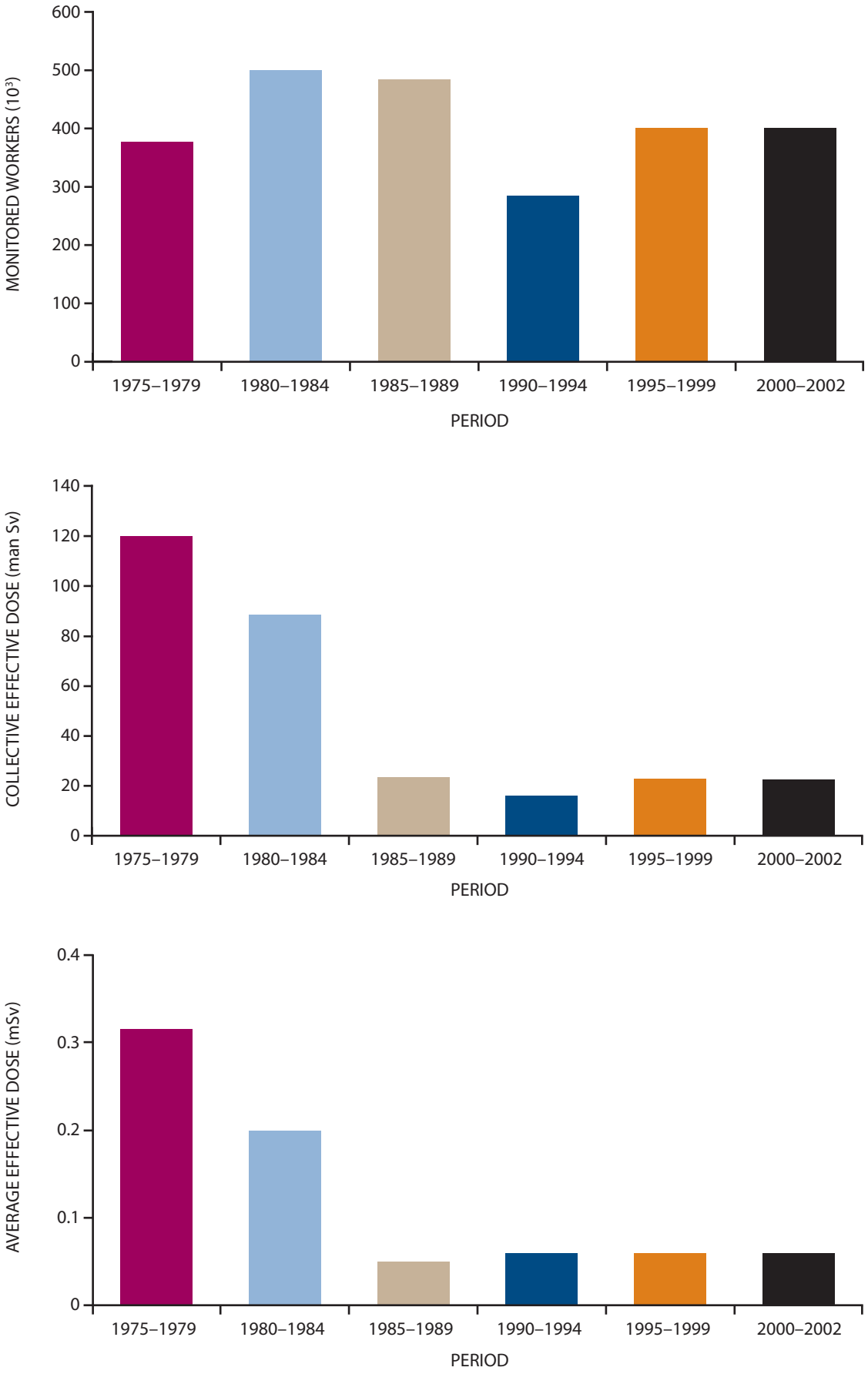


Figure LII. Worldwide trends in occupational exposure due to nuclear medicine
Average annual numbers of monitored workers, and collective effective doses and effective doses to monitored workers

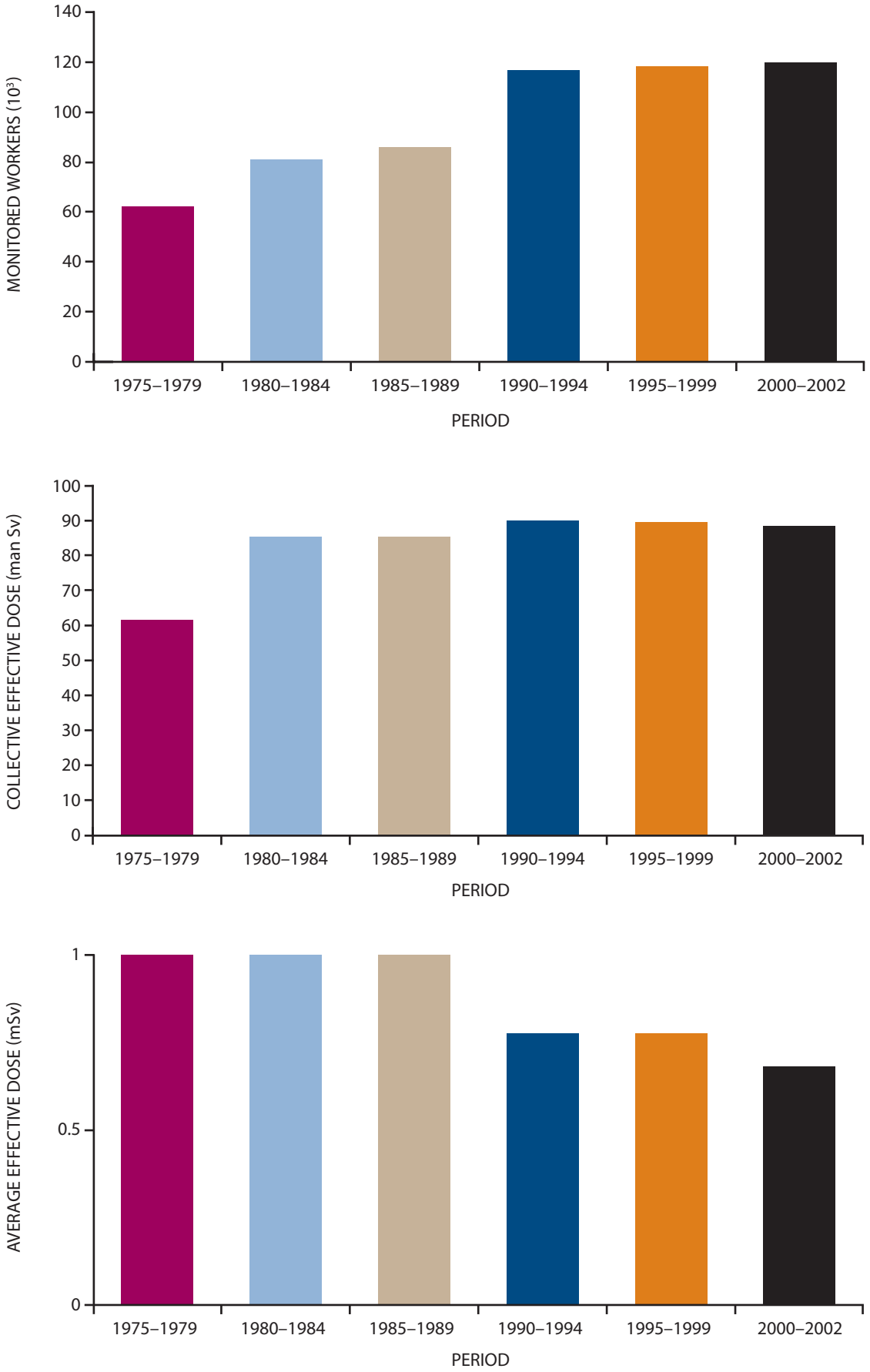
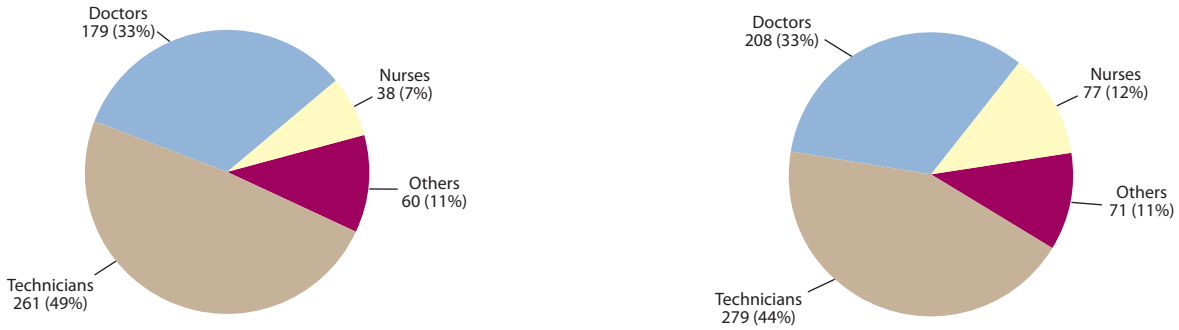


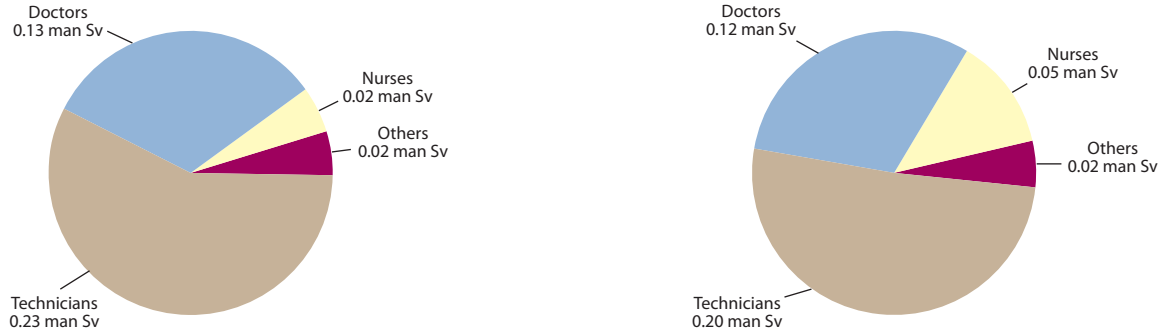
Figure LIII. Occupational exposures due to nuclear medicine in Greece for various job categories for the periods 1995–1999 and 2000–2002

(1995–1999) (2000–2002)

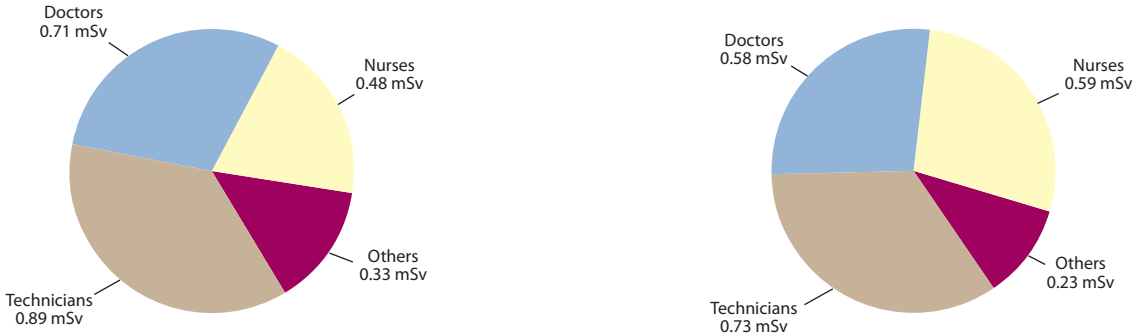
(a) Numbers of monitored workers



(b) Collective effective doses



(c) Average effective doses for monitored workers



(d) Average effective doses for measurably exposed workers

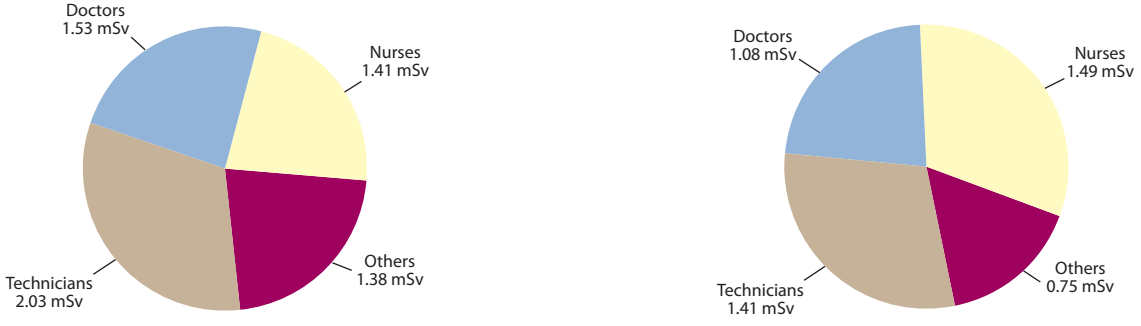


Figure LIV. Worldwide trends in occupational exposure due to radiotherapy
Average annual numbers of monitored workers, and collective effective doses and effective doses to monitored workers

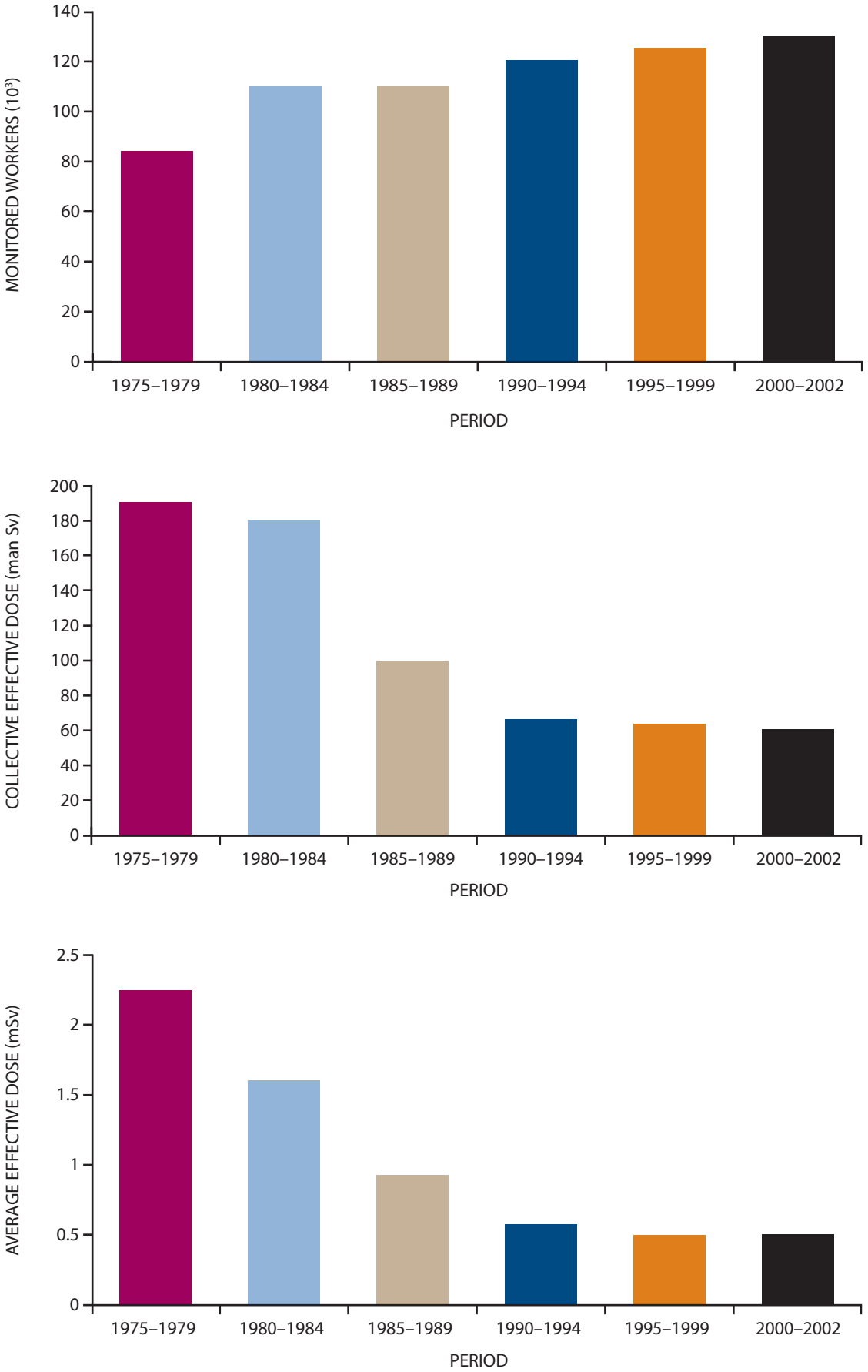


Figure LV. Worldwide trends in occupational exposure due to all medical uses of radiation
Average annual numbers of monitored workers, and collective effective doses and effective doses to monitored workers

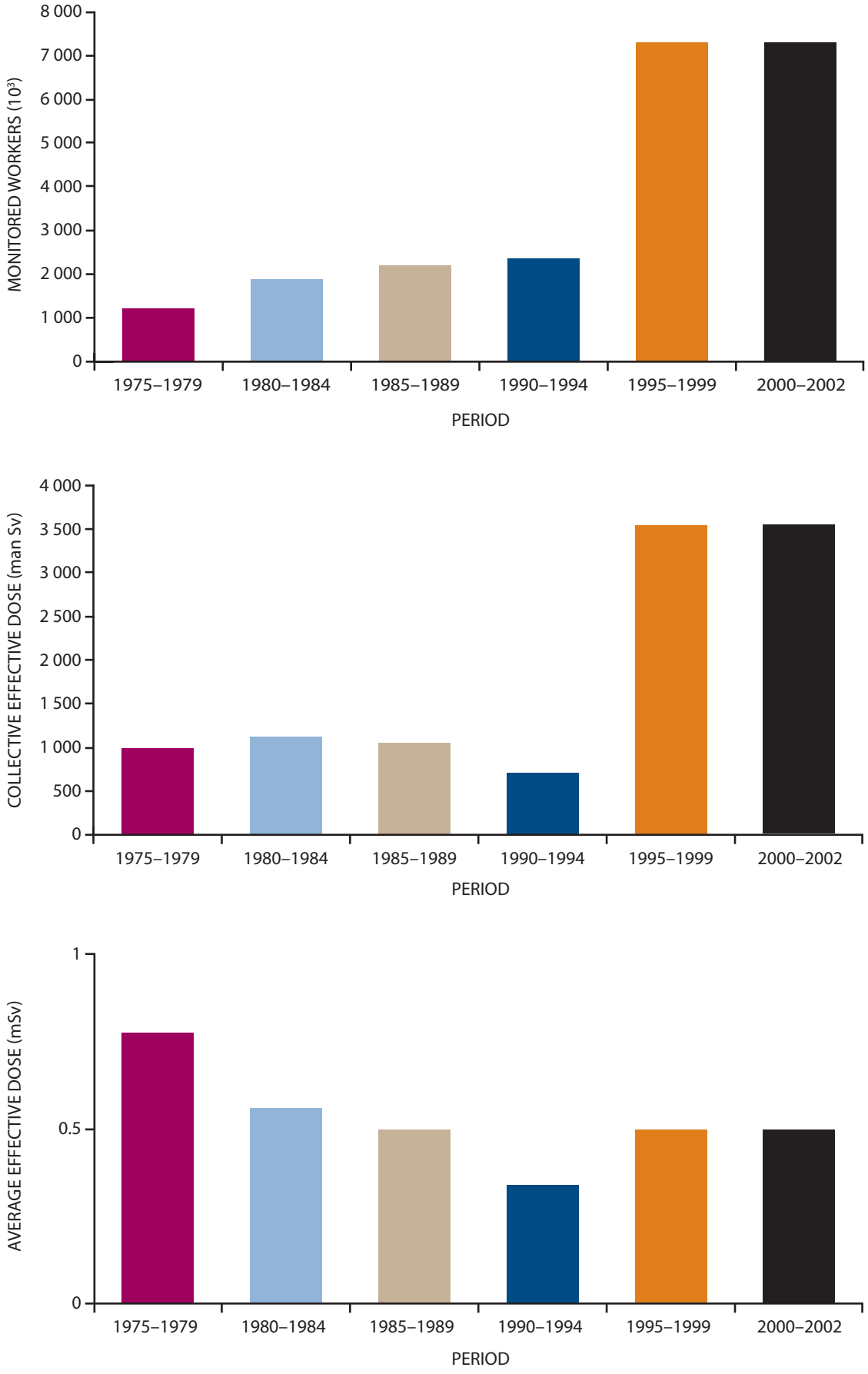


Figure LVI. Trends in occupational exposure due to industrial irradiation in China

Average annual numbers of monitored workers, and collective effective doses and effective doses to monitored workers

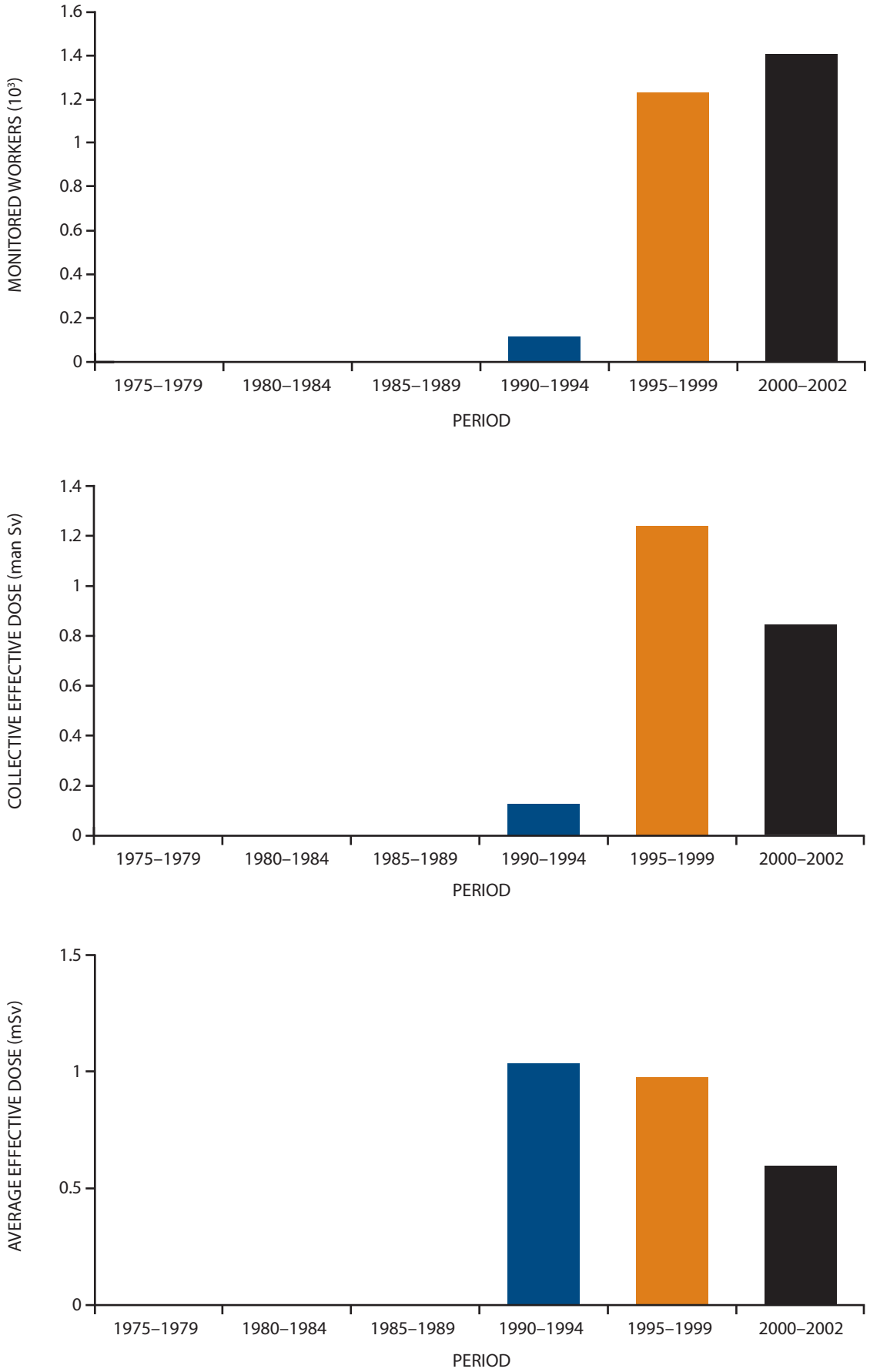


Figure LVII. Worldwide trends in occupational exposure due to industrial radiography

Average annual numbers of monitored workers, and collective effective doses and effective doses to monitored workers

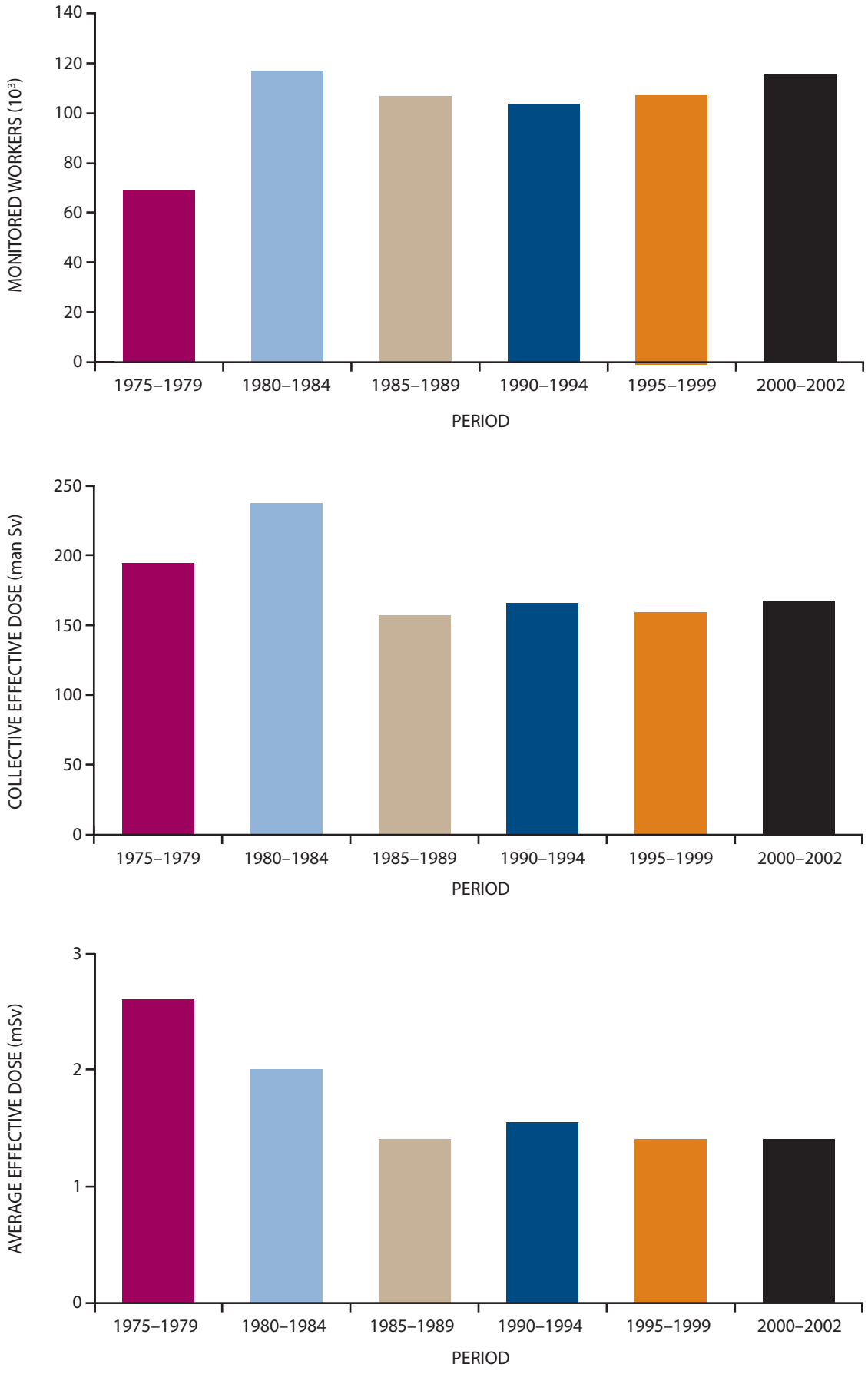


Figure LVIII. Trends in occupational exposure due to luminizing in Switzerland

Average annual numbers of monitored workers, and collective effective doses and effective doses to monitored workers

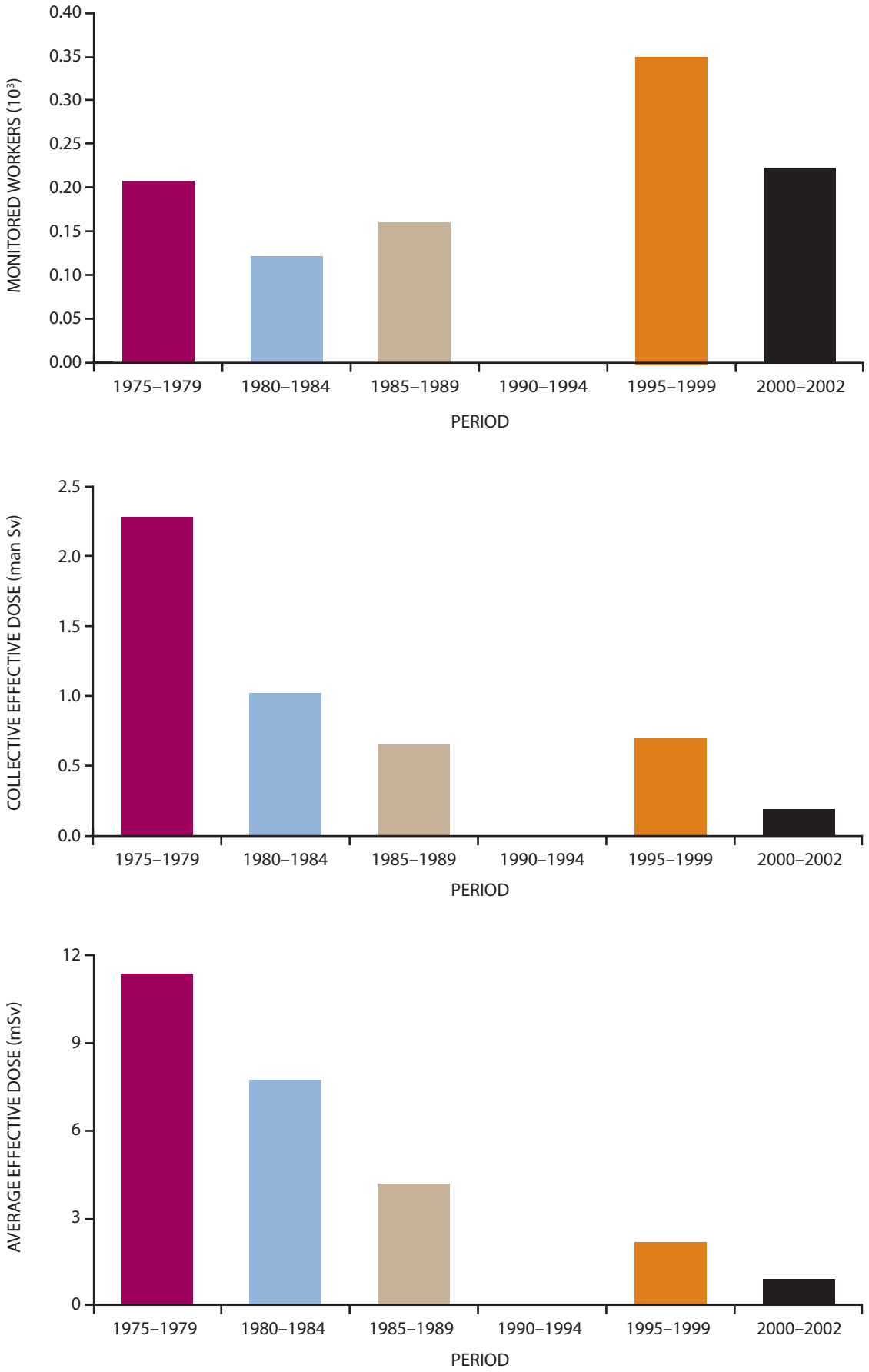


Figure LIX. Worldwide trends in occupational exposure due to radioisotope production

Average annual numbers of monitored workers, and collective effective doses and effective doses to monitored workers

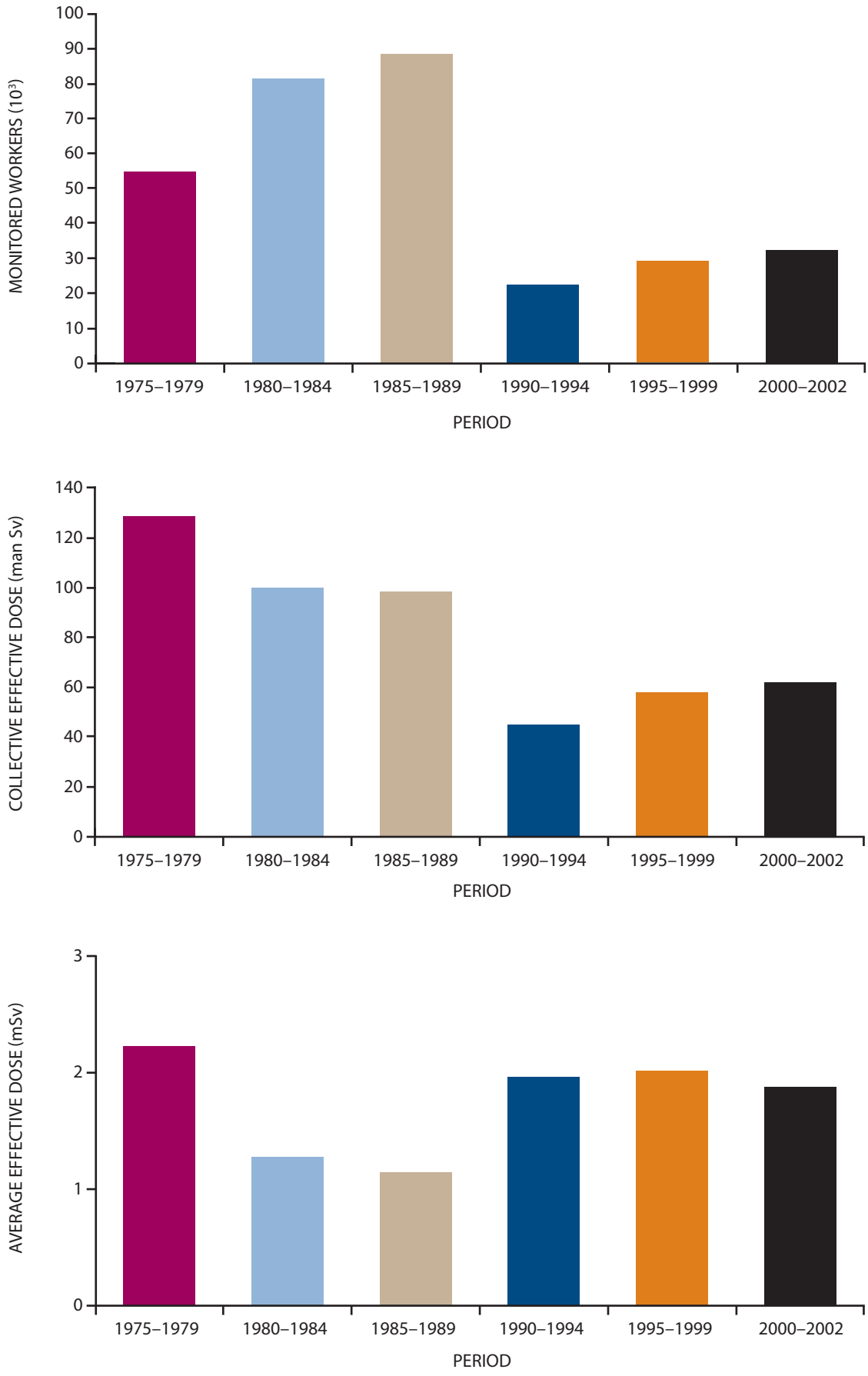


Figure LX. Trends in occupational exposure due to well logging in Canada

Average annual numbers of monitored workers, and collective effective doses and effective doses to monitored workers

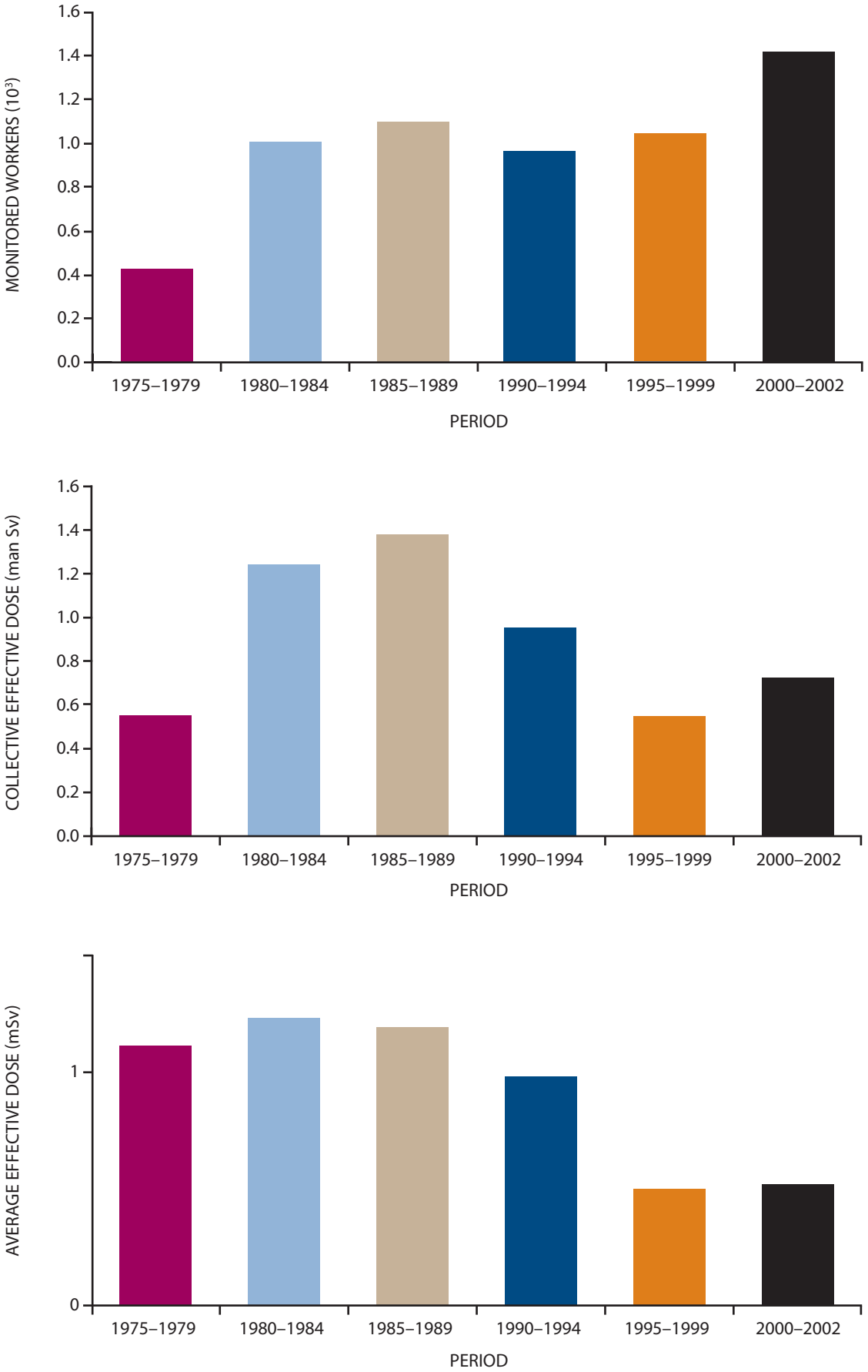


Figure LXI. Trends in occupational exposure due to accelerator operation in Canada

Average annual numbers of monitored workers, and collective effective doses and effective doses to monitored workers

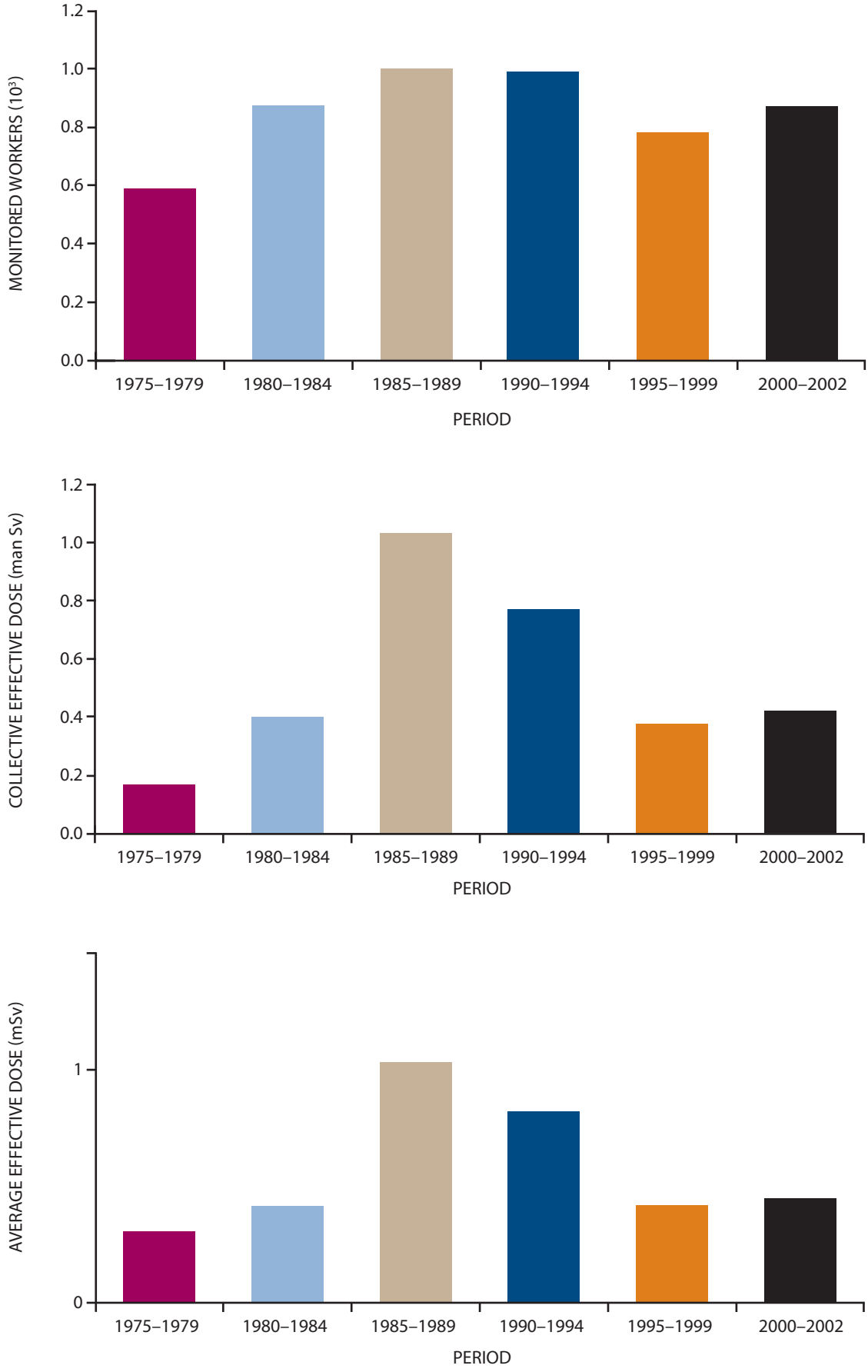


Figure LXII. Worldwide trends in occupational exposure due to all industrial uses of radiation
Average annual numbers of monitored workers, and collective effective doses and effective doses to monitored workers

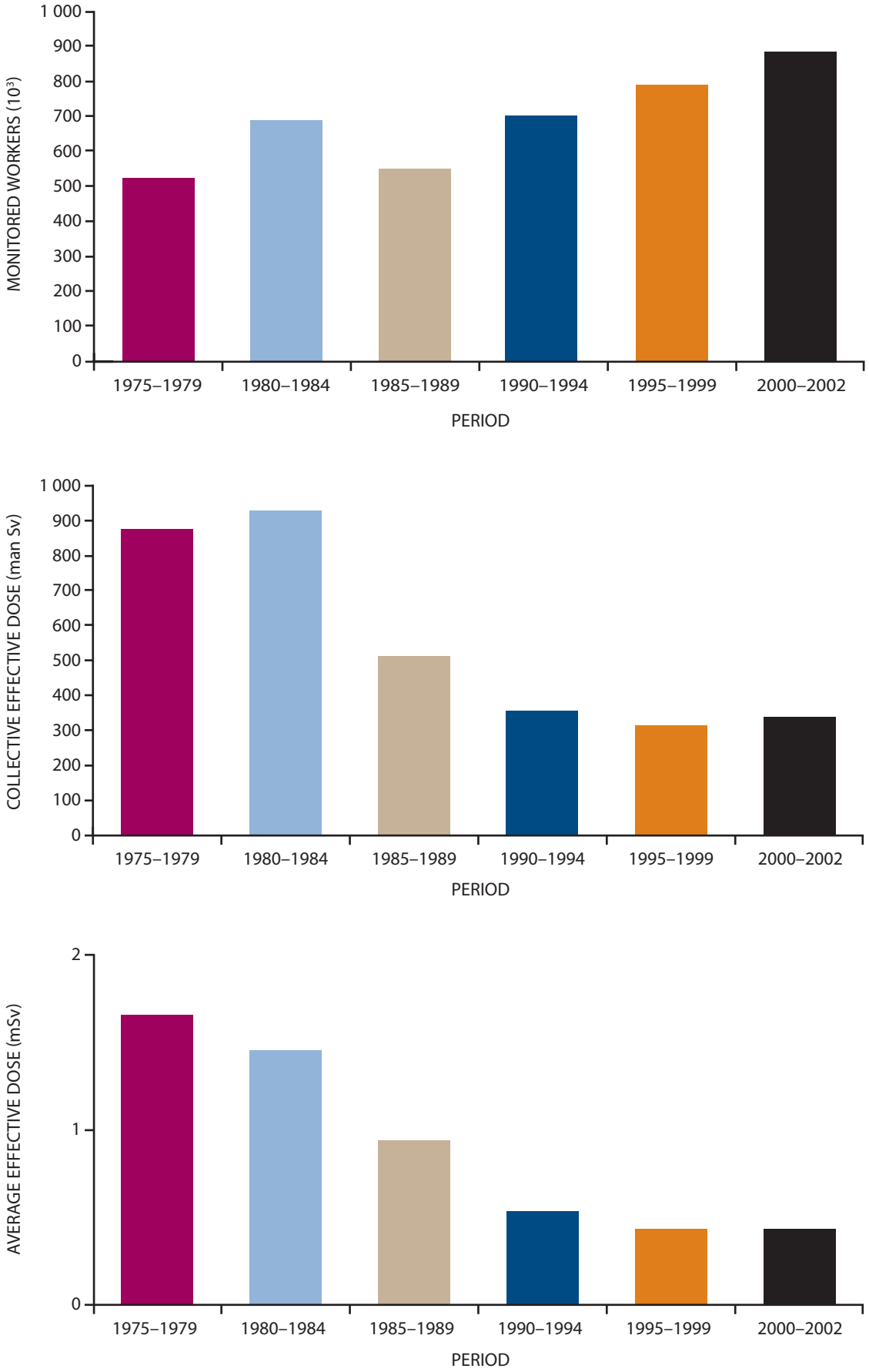


Figure LXIII. Worldwide trends in occupational exposure due to uses of radiation in educational establishments
Average annual numbers of monitored workers, and collective effective doses and effective doses to monitored workers

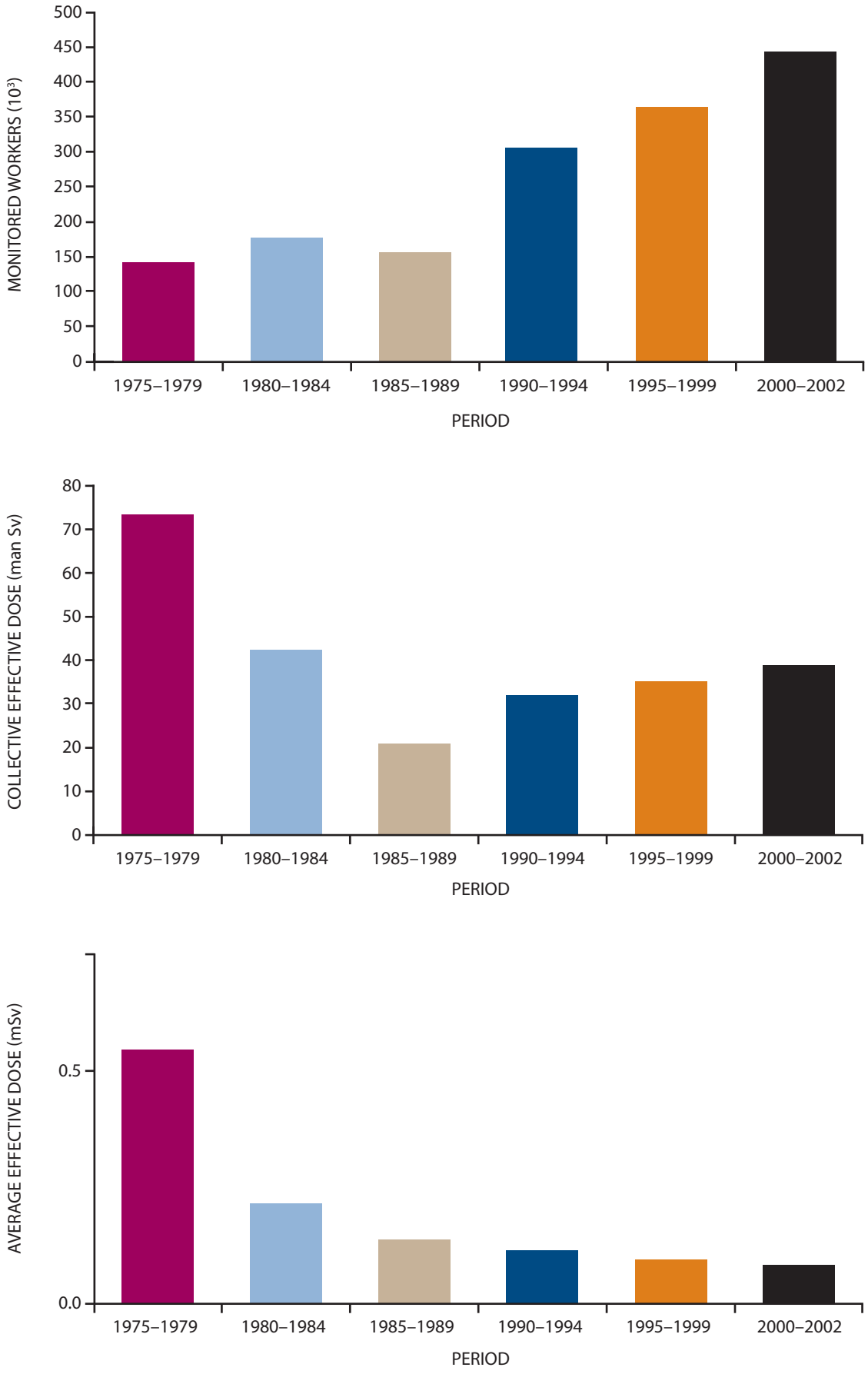


Figure LXIV. Worldwide trends in occupational exposure due to uses of radiation in veterinary medicine
Average annual numbers of monitored workers, and collective effective doses and effective doses to monitored workers

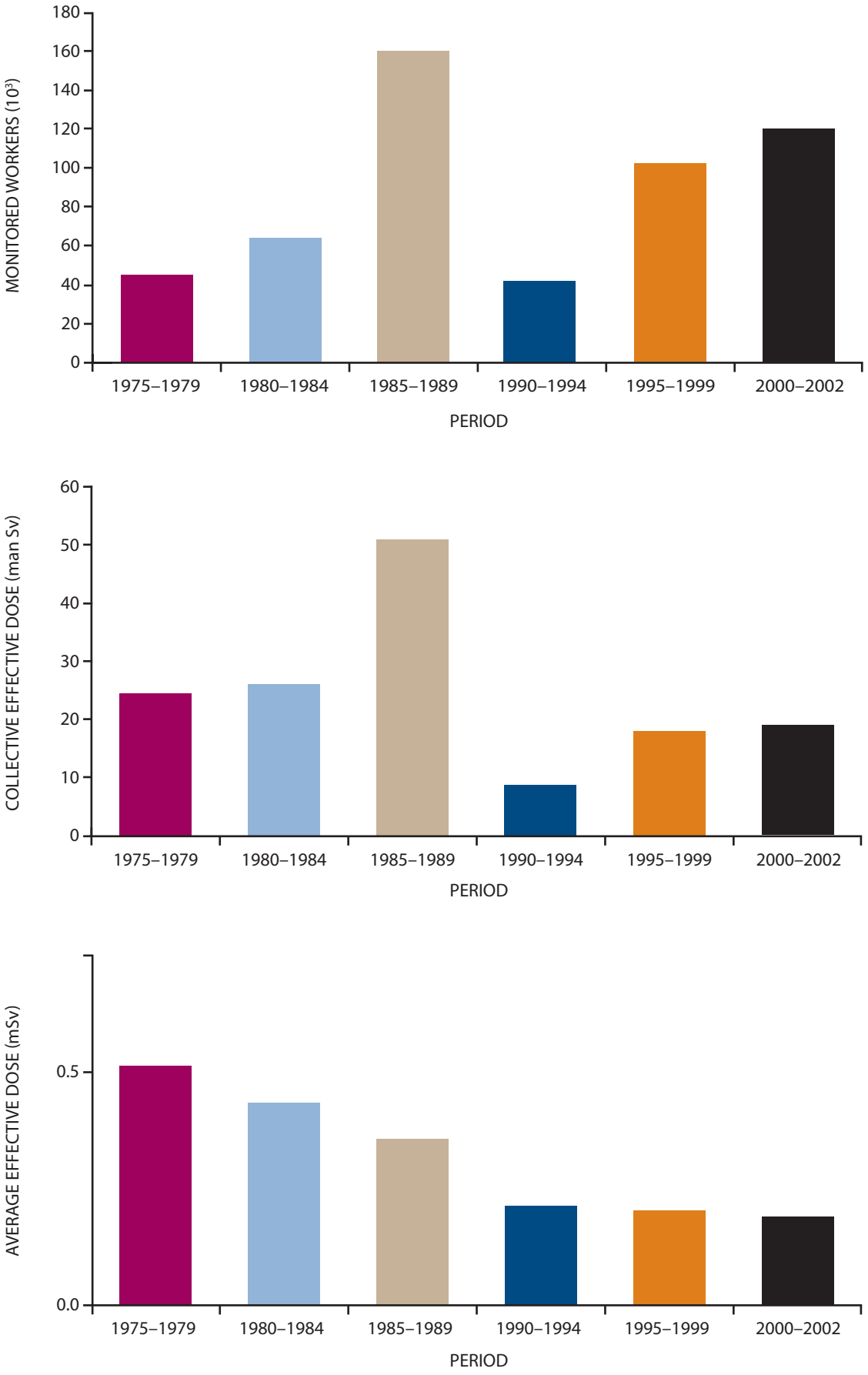


Figure LXV. Fraction of annual doses in three dose ranges for all companies participating in study of occupational doses due to transport in Canada [E2]

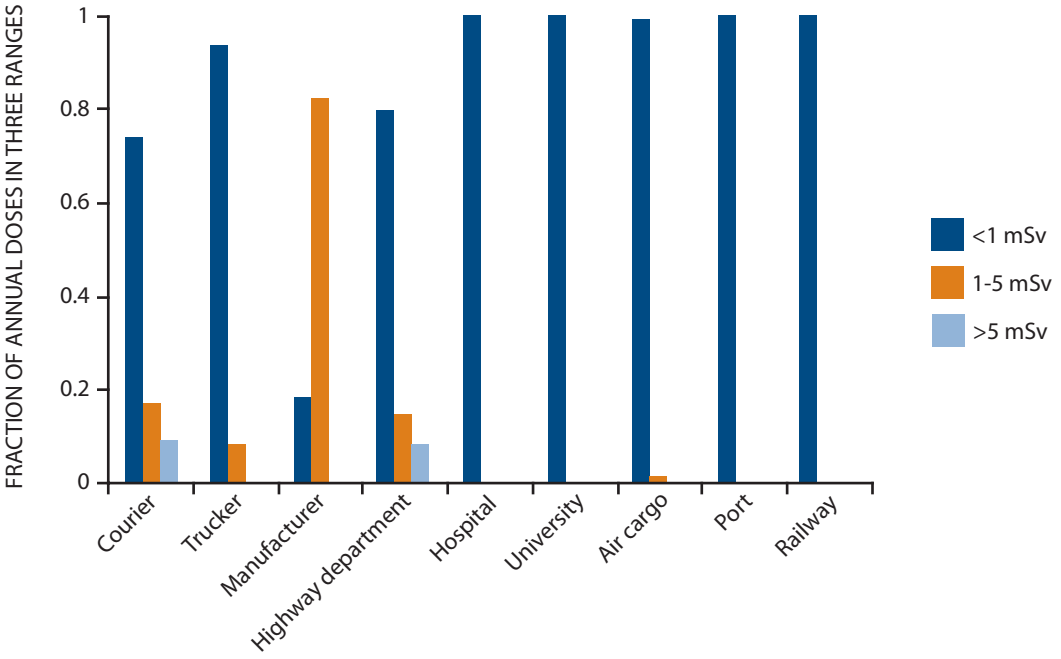


Figure LXVI. Worldwide trends in occupational exposure due to military activities

Average annual numbers of monitored workers, and collective effective doses and effective doses to monitored workers

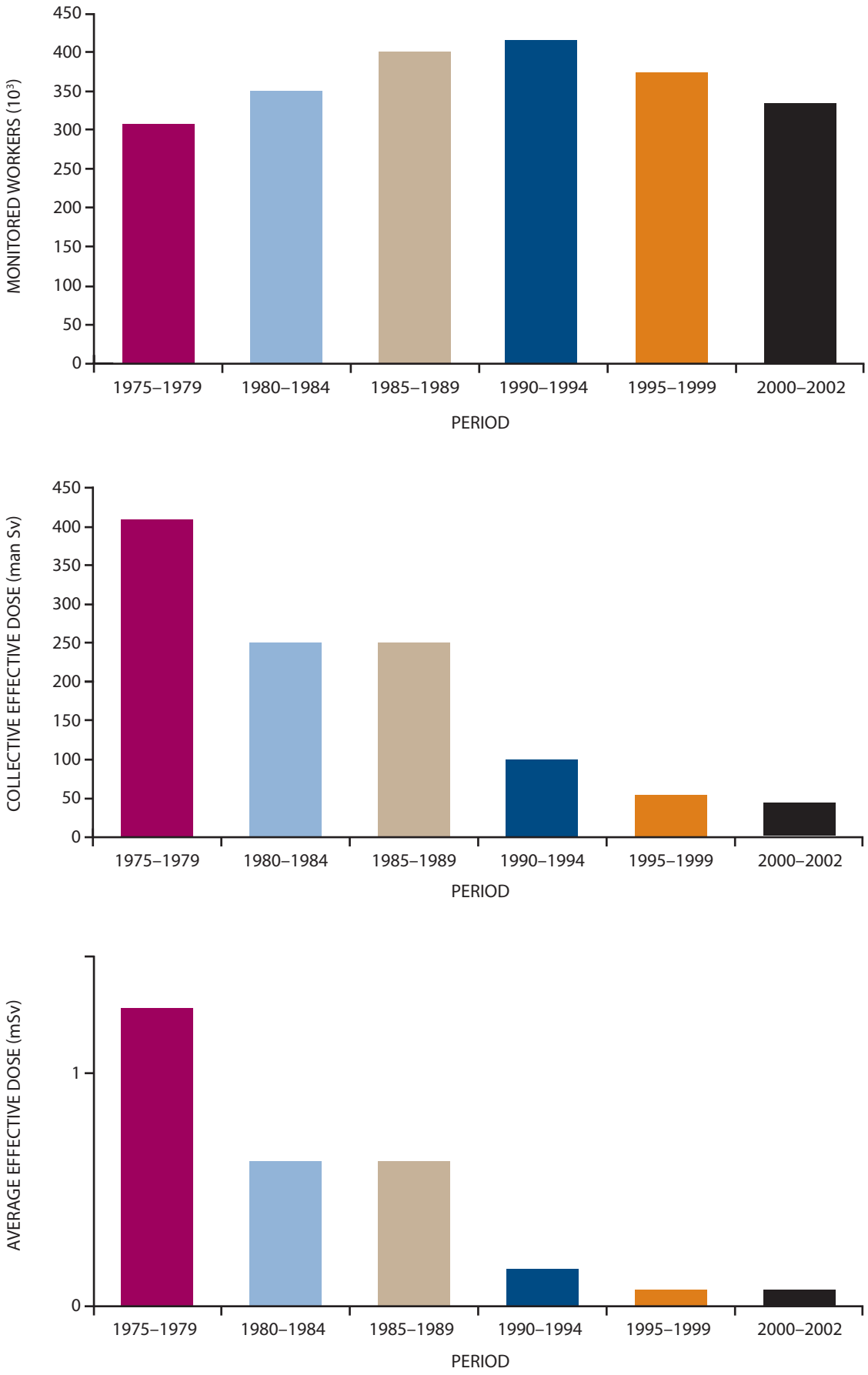


Figure LXVII. Worldwide trends in numbers of monitored workers, and in collective effective doses and effective doses to monitored workers

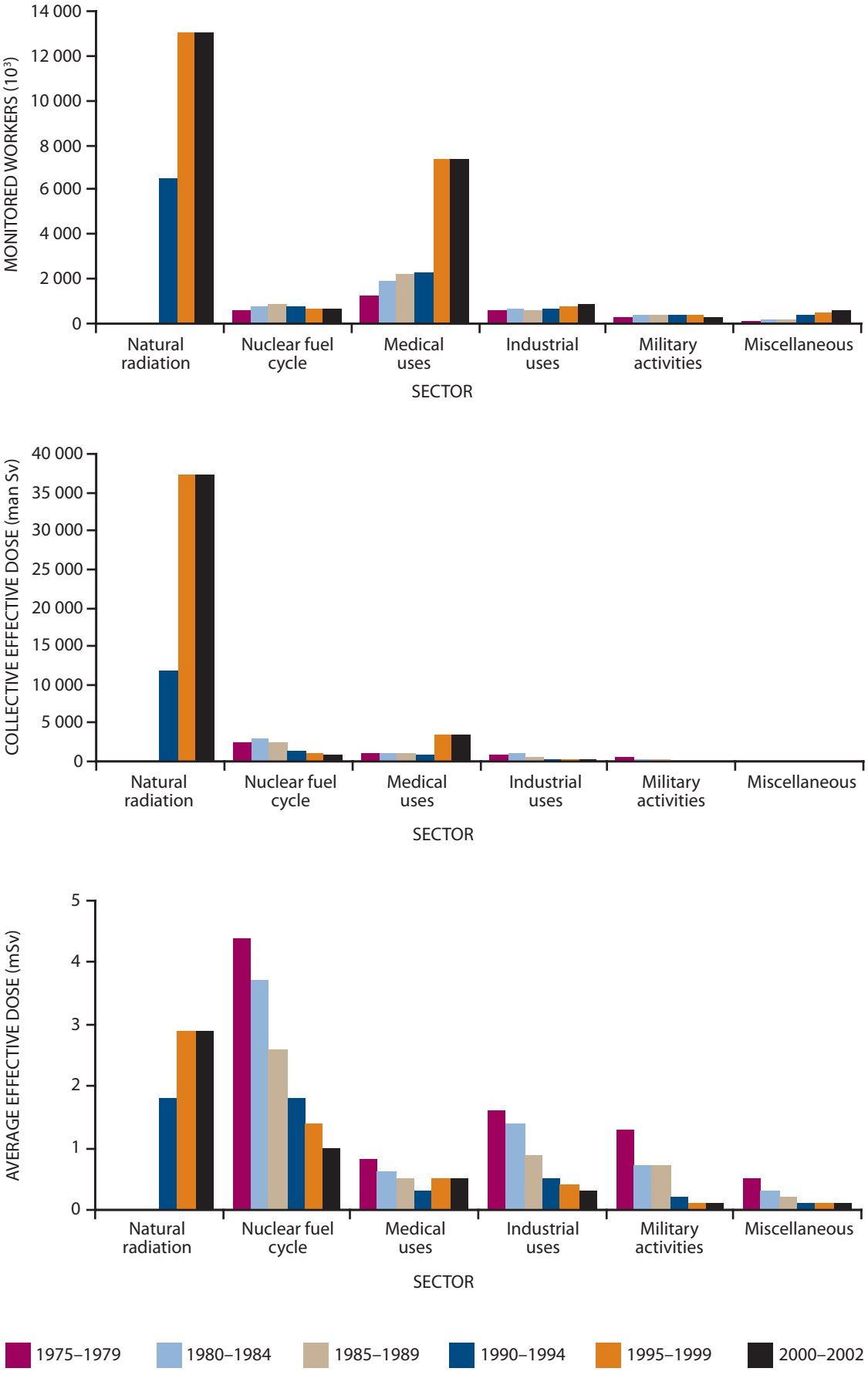


Figure LXVIII. Worldwide trends in occupational exposure due to natural sources of radiation
Average annual numbers of monitored workers, and collective effective doses and effective doses to monitored workers

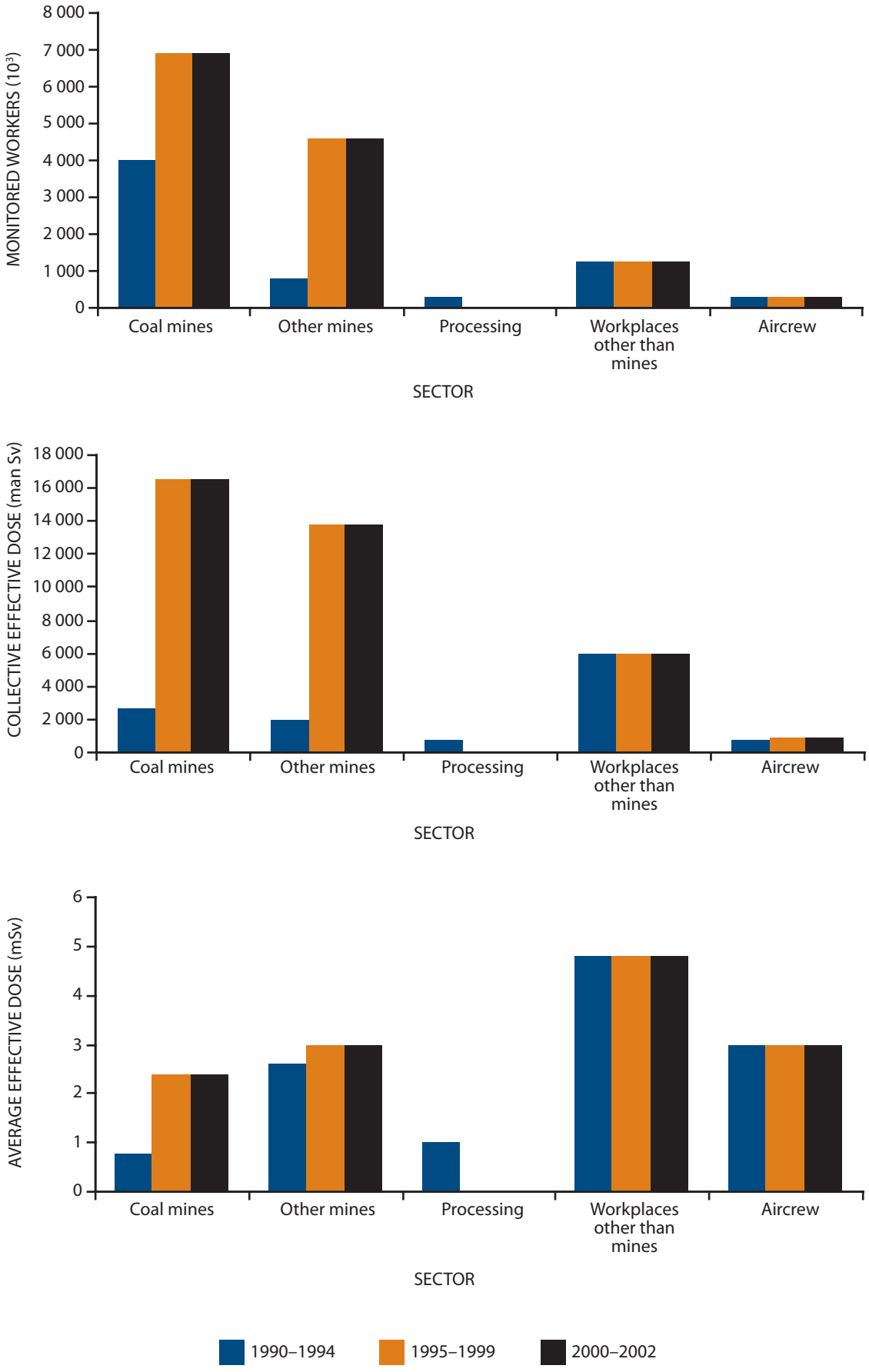
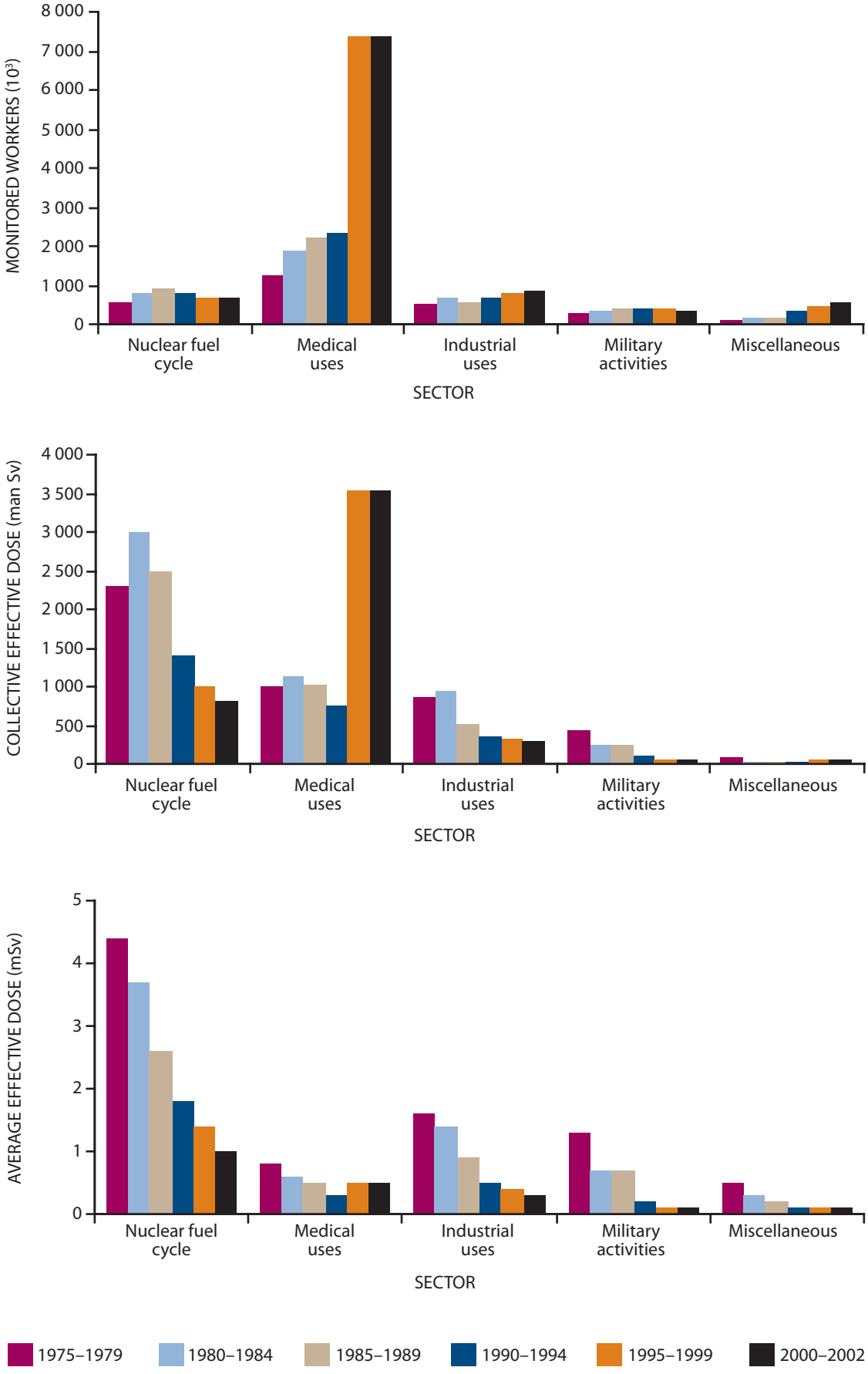


Figure LXIX. Worldwide trends in occupational exposure due to man-made sources of radiation

Average annual numbers of monitored workers, and collective effective doses and effective doses to monitored workers



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