ANNEX E

Occupational radiation exposures

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INTRODUCTION

1. There is 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, such as for 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 its management and control as an occupational hazard.

2. The conventional definition of occupational exposure to any hazardous agent includes all exposures incurred at work, regardless of source [I18]. However, 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 usually taken to mean those exposures that are received at work that can reasonably be regarded as the responsibility of the operating management [I5, I12]. Such exposures are normally also subject to regulatory control, with the requirements for practices as defined by ICRP in its Publication 60 [I12] being applied. The exposures are usually determined by individual monitoring, but sometimes by other methods. An important objective of such determinations is to provide information on the adequacy of protection measures, and they are a key input to operational decisions related to the optimization principle. In addition, they demonstrate compliance with relevant dose limits.

3. The Committee is interested in reviewing the distributions of individual annual effective doses and annual collective effective doses from occupational radiation exposures in various sectors of industry or from various types of source. It is of particular interest to examine the changes that have taken place over time with the introduction of improved practices, new technology, or revised regulations.

4. Data on occupational radiation exposures were given in the UNSCEAR 1977, 1982, 1988, and 1993 Reports [U3, U4, U6, U7]. Differences existed, and indeed still do exist, among countries in the procedures for monitoring and reporting occupational exposures; these differences reflect, among other things, differences in regulatory requirements. As a result, comparisons of data on doses are not always straightforward and may be somewhat limited in scope. Over the years, such comparisons have shed light on these differences, and a number of recommendations have been made. Particular attention was drawn to the need for data on the pattern of dose accumulation over a working lifetime, especially for those occupations in which higher levels of individual exposure are encountered, and to the value of reporting doses in narrower bands of individual dose. Such data are not readily available, however.

5. The main objectives of the analysis of occupational radiation exposures remain, as in the previous assessments of the Committee, as follows:

(a) 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 major practice involving the use of ionizing radiation. This provides a basis for estimating the average individual risks in a workforce and within its subgroups;
(b) 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;
(c) 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 making doses as low as reasonably achievable), new technological developments, modified work practices, and, more generally, radiation protection programmes;
(d) to compare exposures of workers in different countries and to estimate the worldwide levels of exposure for each significant use of ionizing radiation; and
(e) to evaluate data on accidents involving the exposure of workers to levels of radiation that have caused clinical effects.

6. The Committee has evaluated five-year average exposures beginning in 1975. The detailed data presented in this Annex are for 1990–1994, but data for previous periods are provided for comparison. Occupational exposures in each major practice or work activity are reported, indicating trends with respect to the data in the earlier assessments and identifying the main contributors. Exposures from different countries are compared, and worldwide exposures are determined for each category of work in which radiation exposures occur.

7. The data in this Annex were obtained in much the same way as the data for the UNSCEAR 1993 Report [U3]. Data on occupational exposures from man-made sources of radiation (nuclear power, defence activities, and industrial and medical uses of radiation) are systematically collected by many national authorities. The Committee obtained these data by means of a questionnaire, the UNSCEAR Survey of Occupational Radiation Exposures, which it distributed to countries throughout the world. The data have been supplemented by other (usually published) sources of information; for the nuclear power industry, for example, the source is the databank of the Organization for Economic Cooperation and Development/Nuclear Energy Agency (OECD/NEA) [O2, O5]. However, the data set is by no means complete, and procedures have been developed by the Committee to derive worldwide doses from the data available for particular occupational categories (see Section I.E).

8. The data on doses arising in the commercial nuclear fuel cycle are reasonably complete. Where data are missing or incomplete, doses can be calculated from worldwide statistics on capacity and production in the various stages of the fuel cycle. Thus the worldwide annual collective effective dose from a given part of the nuclear fuel cycle is estimated to be the total of the annual collective effective doses from the reported data scaled according to the total worldwide statistic (uranium mined, fuel fabricated, energy generated, etc.).

9. For exposures to radiation in other operations, the calculations are scaled according to the gross domestic product (GDP) of countries. The GDP is reasonably correlated with the level of both industrial activity and medical care in a country. To make the calculations more reliable, the values of GDP are applied to regional data, and the results are summed over all regions. For this purpose, the world was divided into seven regions: the OECD excluding the United States; the United States; eastern Europe and the countries of the former USSR; Latin America; the Indian subcontinent; east and south-west Asia; and the remaining countries.

10. Exposures from natural sources of radiation, with a few exceptions, have generally not been subject to the same degree of control as exposures from man-made sources. The few exceptions are exposures in uranium mines and mills and in practices where purified forms of naturally occurring radioactive substances, such as ^{226}Ra and thorium, are handled.

11. The principal natural sources of radiation exposure of interest other than those that have traditionally been directly related to the work (e.g. those in the mining and milling of uranium ores) are radon in buildings, non-uranium mines and other underground workplaces; cosmic rays at aircraft altitudes; and materials other than uranium or thorium ores that contain significant traces of natural radionuclides. The exposures of individuals in the first two situations are often comparable to, if not in excess of, the exposures currently received from man-made sources. Furthermore, there is some scope for the reduction of these exposures, particularly those from radon. The large number of workers involved, particularly in the mining industry, results in annual collective effective doses that are substantially higher than those from man-made sources of radiation.

I. DOSE MONITORING AND RECORDING PRACTICES

12. A number of difficulties are encountered in determining occupational exposures. External radiation fields may be non-uniform in space and time and may be of various types and a wide range of energies. Internal exposures may also occur. Workers may be frequently exposed, seldom exposed, or hardly exposed at all. The difficulties may be addressed in various ways, as reflected in the variety of monitoring procedures and dose recording practices adopted in countries throughout the world. This topic was addressed in some detail in the UNSCEAR 1993 Report [U3]. However, to the extent that attention still needs to be drawn to it or that changes have occurred that may affect the interpretation of results, the topic is discussed further in this Chapter.

A. QUANTITIES MEASURED

1. Protection quantities

13. The basic physical quantity used in radiological protection is the absorbed dose, D_T, averaged over an organ or defined tissue. The absorbed dose is expressed in the unit gray (Gy), with 1 Gy equal to 1 joule per kilogramme. To account for the type of the radiation and the differences in ionization density, a further quantity has been introduced, the equivalent dose, H_T, which is the average absorbed dose in an organ or tissue multiplied by a dimensionless factor called the radiation weighting factor, w_R. Equivalent dose is expressed in the unit sievert (Sv).

14. The effective dose, E, also expressed in Sv, has been defined to take account of the fact that the probability of stochastic effects for a given equivalent dose varies with the organ or tissue irradiated. The factor by which the equivalent dose in a tissue or organ is weighted is called the tissue weighting factor, w_T, the values being chosen such that the effective dose gives a measure of the radiation detriment irrespective of how that dose was received. In particular, this approach allows effective doses from external and internal exposures to be aggregated.

15. Effective dose and equivalent dose are the basic quantities for radiological protection purposes in which, for example, dose limits are expressed [I12]. The effective dose limit is intended to limit the total health detriment from radiation exposure due to stochastic effects. Limits on equivalent dose are required for skin and the lens of the eye to ensure that deterministic effects are avoided in these tissues. These protection quantities relate, as appropriate, to the sum of the effective or equivalent doses from external sources and the committed effective or equivalent doses from the intake of radionuclides. Dose quantities are discussed in detail in Annex A, "*Dose assessment methodologies*".

2. Quantities for external radiation exposure

16. The basic quantities for physical measurement include particle fluence, kerma, and absorbed dose. They are the quantities used by national standards laboratories.

However, the need for measurable quantities for external radiation exposure that can be related to the protection quantities has led to the development of operational quantities, which provide an estimate of effective or equivalent dose that avoids underestimation and excessive overestimation in most radiation fields encountered in practice.

17. There are three operational quantities of particular interest in the measurement of radiation fields for protection purposes: the ambient dose equivalent, $H^*(d)$; the directional dose equivalent, $H'(d, \Omega)$; and the personal dose equivalent, $H_p(d)$. All these quantities are based on the dose equivalent at a point and not on the concept of equivalent dose. The ambient dose equivalent and the directional dose equivalent are appropriate for environmental and area monitoring, the former for strongly penetrating radiation and the latter for weakly penetrating radiation. The ambient dose equivalent at a point in a radiation field is the dose equivalent that would be produced by the corresponding aligned and expanded field in the ICRU sphere at a depth d on the radius opposing the direction of the aligned field. The directional dose equivalent at a point is the dose equivalent that would be produced by the corresponding expanded field in the ICRU sphere at a depth d on a radius in a specified direction. The concepts of “expanded” and “aligned” fields are given in ICRU Report 39 [I19] to characterize fields that are derived from the actual radiation fields. In the expanded field, the fluence and its angular and energy distribution have the same values throughout the volume of interest as at the actual field at the point of reference. In the aligned and expanded field, the fluence and its energy distribution are the same as in the expanded field, but the fluence is unidirectional.

18. The personal dose equivalent, $H_p(d)$, is the dose equivalent in soft tissue below a specified point on the body at an appropriate depth d. This quantity can be used for measurements of superficial and deep organ doses, depending on the chosen value of the depth in tissue. The depth d is expressed in millimetres, and ICRU recommends that any statement of personal dose equivalent should specify this depth. For superficial organs, depths of 0.07 mm for skin and 3 mm for the lens of the eye are employed, and the personal dose equivalents for those depths are denoted by $H_p(0.07)$ and $H_p(3)$, respectively. For deep organs and the control of effective dose, a depth of 10 mm is frequently used, with the notation $H_p(10)$.

19. Personal dose equivalent quantities are defined in the body and are therefore not directly measurable. They vary from person to person and from location to location on a person, because of scattering and attenuation. However, $H_p(d)$ can be assessed indirectly with a thin, tissue-equivalent detector that is worn at the surface of the body and covered with an appropriate thickness of tissue equivalent material. ICRU recommends that dosimeters be calibrated under simplified conditions on an appropriate phantom [I20].

20. The relationship between the physical, protection, and operational quantities is illustrated in Figure I. They are discussed more fully in ICRP Publication 74 [I16], which provides conversion coefficients for use in radiological protection against external radiations. It was concluded that there is an acceptable agreement between the operational and protection quantities for radiation fields of practical significance when the operational quantities are based on the Q/LET relationship given in ICRP Publication 60 [I12].

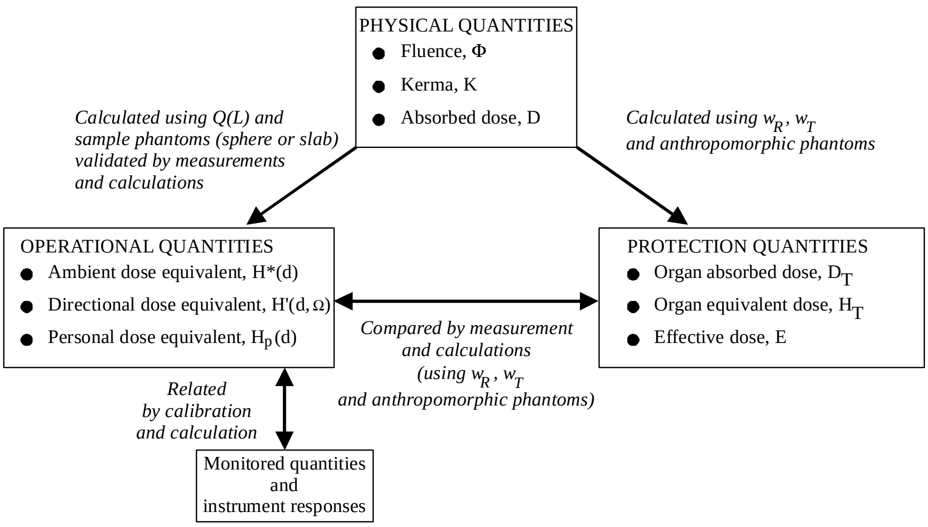

Figure I. Relationship of quantities for radiological protection monitoring purposes [I16].

21. In most practical situations, dosimeters provide reasonable approximations to the personal dose equivalent, $H_p(d)$, at least at the location of the dosimeter. When the exposure of the body is relatively low and uniform, it is common practice to enter the dosimeter reading, suitably calibrated, directly into the dose records as a surrogate for effective dose. However, because the personal dose equivalent generally overestimates the effective dose, this

practice results in overestimated recorded and reported doses, with the degree of overestimation depending on the energy of the radiation and the nature of the radiation field. For many practical situations involving relatively uniform exposure to fairly high-energy gamma radiation, the degree of overestimation is modest; for exposure to low-energy gamma or x radiation, the overestimation can be substantial. For photon energies below ~50 keV, the effective dose can be overestimated by a factor of 2, depending on the orientation of the body.

22. For exposure to spatially variable radiation fields or where there is partial shielding of the body or extreme variations in the distances of parts of the body from the source, the relationships between the dosimeter measurement and the effective dose are more variable and complex. Where the circumstances so justify, additional measurements or theoretical analysis have been used to establish reliable relationships on a case-by-case basis for the exposure conditions of interest. The direct entry of dosimeter measurements into dose records in these more complex situations (or the use of very simple and deliberately cautious assumptions to establish the relationships between the two quantities) leads, in general, to overestimates in the recorded exposures. Where such practice has been adopted in the recording of doses, care is needed in their interpretation, in particular when they are being compared with doses arising elsewhere. The information available to the Committee is generally not sufficient to allow the exercise of such care in interpreting recorded values.

23. For its previous assessments, the Committee adopted the convention that all quantitative results reported by monitoring services represent the average absorbed dose in the whole body (or the effective dose). It is further assumed that the dose from normal natural background radiation has been subtracted from the reported results, although this was not always clear from the responses to the questionnaire. It is also assumed that medical radiation exposures have not been included. The Committee recognized that it is almost always the reading from the dosimeter, suitably modified by calibration factors, that is reported, without considering its relationship to the absorbed doses in the various organs and tissues of the body or to the effective dose. This is still regarded as a reasonable convention, in particular as most data are for external exposure of the whole body to relatively uniform photon radiation of moderately high energy. Where exposure of the body is very non-uniform (especially in medical practice) or where exposure is mainly to low-energy radiation, the use of this convention may result in an overestimate of effective doses, which then needs appropriate qualification. Because the relationship between the reported dosimeter reading and the average absorbed dose in the whole body (or the effective dose) varies with the circumstances of the exposure, caution needs to be exercised when aggregating or directly comparing data from very dissimilar types of work. The reported data are appropriately qualified where the adoption of the above convention could lead to a significant misrepresentation of the actual doses.

3. Quantities for internal radiation exposure

24. Radionuclides taken into the body will continue to irradiate tissue until they have been fully excreted or have fully decayed. The committed effective dose for occupational exposure, E(50), is formally defined as the sum of the products of the committed organ or tissue equivalent doses and the appropriate organ or tissue weighting factors, where 50 is the integration time in years following intake. The committed equivalent dose, $H_T(50)$, is formally defined as the time integral of the equivalent dose rate in a particular tissue or organ that will be received by an individual following intake of radioactive material into the body, where 50 is, again, the integration time in years following intake.

25. In the calculation of E(50) and, where appropriate, of $H_T(50)$, the dose coefficient is frequently used. For occupational exposure, this is the committed effective dose per unit acute intake, e(50), or committed tissue equivalent dose per unit acute intake, $h_T(50)$, where 50 is the time period in years over which the dose is calculated. The unit is sievert per becquerel.

26. ICRP has recommended that the annual limit on intake (ALI) should be based on a committed effective dose of 20 mSv [I12]. The annual limit on intake (Bq) can then be obtained by dividing the annual average effective dose limit (0.02 Sv) by the dose coefficient, e(50) ($Sv\ Bq^{-1}$). The dose coefficients for occupational exposure for inhalation and ingestion of radionuclides based on the radiation and tissue weighting factors in ICRP Publication 60 [I12] and the new Human Respiratory Tract Model for Radiological Protection [I14] are given in ICRP Publication 68 [I15].

4. Total effective dose

27. The total effective dose, E(t), during any time period, t, can be estimated from the following expression:

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

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 from radionuclide j, integrated over 50 years; $I_{j,inh}$ is the intake of radionuclide j by inhalation during time period t; $e_{j,ing}(50)$ is the committed effective dose per unit activity intake by ingestion from radionuclide j, integrated over 50 years; $I_{j,ing}$ is the intake of radionuclide j by ingestion during time period t.

28. The conversion coefficients for use in radiological protection against external radiation are given in ICRP Publication 74 [I16]. 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 [I15], which takes account of the tissue

weighting factors in ICRP Publication 60 [I12] and the new lung model in ICRP Publication 66 [I14]. It is assumed that the data provided to the Committee will have been based on these conversion coefficients. The parameters for radon are given below.

5. Special quantities for radon

29. Special quantities and units are used to characterize the concentration of the short-lived progeny of both ^{220}Rn (commonly known as thoron) and ^{222}Rn (commonly known as radon) in air and the resulting inhalation exposure (see ICRP Publication 65 [I13]).

30. The potential alpha energy, ε_p, of an atom in the decay chain of radon or thoron is the total alpha energy emitted during the decay of this atom to ^{206}Pb or ^{208}Pb, respectively. The SI unit is joule, J; MeV is also used. The potential alpha energy concentration, c_p, of any mixture of short-lived radon or thoron decay products in air is the sum of the potential alpha energy of these atoms present per unit volume of air, and the SI unit is J m^{-3}. The potential alpha energy concentration can also be expressed in terms of the unit working level (WL), which is still used in some countries. One WL is defined as a concentration of potential alpha energy of 1.30 10^{8} MeV m^{-3}. The potential alpha energy concentration can also be expressed in terms of the equilibrium equivalent concentration, c_{eq}, of the parent nuclide, radon. The equilibrium equivalent concentration for a non-equilibrium mixture of radon progeny in air is that activity concentration of radon in radioactive equilibrium with its short-lived progeny that has the same potential alpha energy concentration, c_p, as the non-equilibrium mixture. The SI unit of the equilibrium equivalent concentration is Bq m^{-3}.

31. The exposure of an individual to radon or thoron progeny is determined by the time integral of the potential alpha energy concentration in air or of the corresponding equilibrium equivalent concentration. In the former case, it is expressed in the unit J h m^{-3} and in the latter, in the unit Bq h m^{-3}. The potential alpha energy exposure is also often expressed in the historical unit working level month (WLM). Since this quantity was introduced for specifying occupational exposure, one month was taken to be 170 hours. Since 1 MeV = 1.602 10^{-13} J, the relationship between the historical and the SI unit is 1 WLM = 3.54 10^{-3} J h m^{-3}. The factor for converting from WLM to effective dose has been the subject of some debate. The Committee has adopted a radon dose coefficient of 9 nSv (Bq h m^{-3})$^{-1}$. However, the ICRP derived a conversion convention of 5 mSv (WLM)$^{-1}$ or 6 nSv (Bq h m^{-3})$^{-1}$, which was used in the questionnaire sent to national authorities in gathering information for the Annex. As a result of this difference, the data in this Annex for radon exposure situations underestimate the doses by about 30%.

B. MONITORING PRACTICES

32. For many reasons, worker monitoring practices differ from country to country, from industry to industry, and sometimes even from site to site within a given industry. Some of these differences stem from historical, technological, cost, or convenience considerations. In general, monitoring practice is such that more workers are individually monitored than is strictly necessary to meet regulatory requirements, with the consequence that only a fraction of those monitored receive measurable doses. Although these differences may not seriously affect the quality of the data, they could lead to some difficulties in making valid comparisons of results.

33. It is convenient to subdivide monitoring programmes into a number of categories. Routine monitoring is associated with continuing operations and is intended to demonstrate that the working conditions, including the levels of individual dose, remain satisfactory and meet regulatory requirements. This sort of monitoring is largely confirmatory in nature, but it underpins the overall monitoring programmes that should be undertaken to control occupational exposure. The most common type of routine monitoring is that undertaken using passive devices, such as film badges or TLDs. Such dosimeters are generally worn by personnel for a set period, and at the end of this period they are read and the doses recorded. In the main, the information used in this Annex comes from such monitoring programmes, although the approaches adopted and the degree of quality control exercised over the measurements vary from country to country.

34. To obtain a more up-to-date understanding of worker exposures, additional task-related monitoring is often undertaken. The intention of such monitoring is to provide data to support immediate decisions on the management of operations and optimization of protection. Task-related monitoring is usually based on some type of direct-reading dosimeter, such as a digital electronic dosimeter or a quartz-fibre electroscope, although multi-element TLD systems are also used. Some examples are given in this Annex.

35. Special monitoring may also be conducted when deemed necessary. It is investigative in nature and typically covers a situation in the workplace where insufficient information is available to demonstrate adequate control. It is intended to provide detailed information that will elucidate any problems and define future procedures.

36. ICRP indicates [I12] that three important factors should 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 dose and intakes, and the complexity of the measurement and interpretation procedures that make up the monitoring programme. In practice, it is usual for all those who are occupationally exposed to external radiation to be individually monitored (i.e. to wear personal dosimeters). When doses are consistently low or predictable, other

methods of monitoring are sometimes used, as in the case of aircrew where doses can be calculated from flight rosters. The third factor results in an approach to the monitoring for external radiation that is different from that for intakes and the resulting committed effective dose.

1. External radiation exposure

37. The approach followed in many countries is to monitor the external radiation exposures of all individuals who work routinely in designated areas. However, on the basis of the recommendations of ICRP [I10], a distinction has often been made in monitoring programmes between those who can exceed 3/10 of the relevant dose limit and those who are most likely not to exceed. While individual monitoring may well have been carried out for those in the second category, the difference in monitoring lies largely in the degree of quality control that is exercised over the measurement. For the Committee, it is important to know whether doses to both groups of workers have been reported to it.

38. Monitoring programmes usually specify how and where personal dosimeters are to be worn 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 $H_p(10)$.

39. Where lead aprons are used in medical radiology, 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 significant, such as in interventional radiology, two dosimeters are sometimes used, one worn under the lead apron and the other worn outside. The purpose of the second dosimeter is to assess the contribution to the effective dose of irradiation of unshielded parts of the body [N6]. Where doses are low and individual monitoring is only intended to give an upper estimate of exposure, single dosimeters may have been worn outside the apron. Measurements made on phantoms using x-ray beams of 76 and 104 kVp have shown that estimates of the effective dose without the lead apron were within 20% of expected values; estimates with the dosimeter worn on the waist underneath the lead apron were lower than the expected values [M1]. The results suggest that accurate estimation of the effective dose from personal dosimeters under conditions of partial body exposure remains problematic and is likely to require the use of multiple monitors, which is not often done. Differing monitoring practices in medical radiology may therefore affect the validity of any comparisons of data acquired.

40. The choice of dosimeter will depend on the objectives of the monitoring programme and on the method of interpreting the data to be used. In practice, the basic choice for penetrating radiation has usually been between a dosimeter giving information on the personal dose equivalent at 10 mm depth and a discriminating device giving some indication of the types of radiation and their effective energies. For a wide range of energies, TLDs with detectors that exhibit little energy dependence of tissue dose response and are covered with tissue-equivalent filters of appropriate thicknesses are an example of the former. Multi-element dosimeters using either photographic film or thermoluminescent material, with filters of different atomic numbers and thicknesses, are an example of the second type.

41. The quality and accuracy of personal electronic dosemeters is improving rapidly, and in a few countries they have already been approved for formal dose assessment for some types of radiation to meet regulatory requirements. The approvals have tended to be limited to specific groups of workers [C2], but the pace of development is such that they are being considered as alternatives to photographic film and TLDs. They offer a low threshold limit of detection and a digital read-out.

42. Personal dosimeters that respond to neutrons over the complete energy range of interest are not available, and some of the current methods of assessment may be relatively expensive and time-consuming. Where the contribution to effective dose from neutrons is small compared with that from photons, the dose is sometimes determined by reference to the photon dose and an assumed ratio of the two components. Alternatively, use is made of measurements in the workplace environment and an assumed occupancy.

43. Monitoring for incident thermal and epithermal neutrons is performed using detectors with high intrinsic sensitivity to thermal neutrons (e.g. some TLDs) or detectors sensitive to other types of radiation (photons and charged particles) and a converter. Neutron interactions in the converter produce secondary radiations that are detectable by the dosimeter. The most common example of the latter technique is the film badge used with a cadmium filter. Some dosimeters have been designed such that they respond, in the main, to thermal and epithermal neutrons produced in the wearer's body by moderation and scatter of higher energy neutrons incident on the body. These "albedo" neutron dosimeters have good response characteristics up to 10 keV neutron energy and, by normalization appropriate to the workplace field, are used where the neutron personal dose equivalent is dominated by neutrons outside this energy range. The normalization process is critically dependent on the neutron spectrum, and if this is not well known or is variable, significant errors may result.

44. The assessment of personal dose equivalents from fast neutrons is carried out by means of nuclear emulsion detectors, bubble detectors, or track-etch detectors (e.g. poly-allyl diglycol carbonate, PADC). Nuclear emulsion dosimeters can measure neutrons at thermal energies and at energies above 700 keV. They have the disadvantages of being relatively insensitive to neutrons with intermediate energies and being sensitive to photons, and they suffer

from fading. Bubble detectors respond to fast neutrons from 100 keV upwards and have the advantage that they are direct-reading, non-sensitive to photons, and reusable, but they have the disadvantage of being temperature- and shock-sensitive. Track-etch detectors based on PADC respond to fast neutrons from about 100 keV upwards.

45. There is a highly complex relationship between the exposure to radiation and the effective dose. Models are required that are intended to give results that are not likely to underestimate the consequences of exposure, though without overestimating them excessively. This is the objective of the operational quantities.

46. In the workplace, the dose rate in air varies as a function of position and time. In the body, the equivalent dose in an organ or tissue is related to the dose equivalent at the surface by factors such as the type and quality of the radiation, the non-uniformity of the field, the orientation of the worker relative to the field, and the position and composition of the organs and tissues within the body. Several of these factors will be functions of both time and position in the workplace.

47. A dosimeter worn on the surface of the body is best regarded as a sampling device. It provides a measure of the dose equivalent to the skin and underlying tissue in the immediate vicinity of the dosimeter. A personal dosimeter on a phantom can be calibrated in terms of the measured or calculated values of the personal dose equivalent $H_p(d)$. When worn on the body of a person facing a unidirectional field of radiation, it will indicate the personal dose equivalent. Where a worker moves about the workplace, resulting effectively in a multidirectional field, a personal dosimeter will provide an adequate measure of the personal dose equivalent. Furthermore, the personal dose equivalents will, for most combinations of exposure, overestimate the effective dose. In some cases, the overestimation may be substantial.

48. There are three main areas of uncertainty in individual monitoring for external radiation:

(a) that which is inherent in dose calibrations;
(b) that due to the measurement of the operational quantity $H_p(10)$ as compared with the reading of an ideal dosimeter for the measurement of the quantity when worn on the same point on the body; and
(c) that which occurs if the dosimeter is not worn at the appropriate point on the body.

These uncertainties and how they are dealt with by the dosimetry services could also have an impact on the comparisons made in this Annex.

49. Many countries appear to follow the guidance given in ICRP Publication 35 [I10]. This defines acceptable uncertainties in routine monitoring for external radiation. Near the dose limits, the recommendation is that the uncertainty should be within a factor of 1.5 in either direction. Some relaxation is allowed at lower doses. It has been shown that these recommendations can be met by the majority of personal dosimeters currently in use, as far as the measurement of $H_p(10)$ is concerned [M2]. It must be appreciated, however, that the relationship between $H_p(10)$ and E introduces further errors, for example for photons. These are relatively small at higher photon energies (e.g. >0.5 MeV), but large overestimates can occur at lower energies, up to a factor of 5 at 10 keV.

2. Internal radiation exposure

50. There are three approaches to the determination of intake and internal dose:

(a) by quantification of exposure to radioactive materials in terms of their time-integrated air concentration via air sampling techniques;
(b) by the determination of internal contamination via direct *in vivo* measurements (*in vivo* methods include direct measurements used for assessing gamma and x-ray emitters and measurements of bremsstrahlung, by methods such as whole-body, thorax, skeleton, and thyroid counting); and
(c) by the measurement of activity in *in vitro* biological samples (*in vitro* methods are usually based on analysis of urine or faecal samples).

In practice, the approach adopted for a situation will depend on the abilities of the various options to indicate doses in that particular situation.

51. The choice between the three approaches is determined by the radiation emitted by the radionuclide; the biokinetic behaviour of the contaminant; its retention in the body, taking into account both biological clearance and radioactive decay; the required frequency of measurements; and the sensitivity, availability, and convenience of the appropriate measurement facilities. The most accurate method in the case of radionuclides emitting penetrating photon radiation is usually *in vivo* measurements. However, even when this method can provide information on the long-term accumulation of internal contamination, it may not be sufficient for assessing committed dose due to a single year's intake. The assessment may also need data from air monitoring. In many situations, therefore, a combination of methods is used. For radon dose assessments, however, air monitoring (individual or area) is the only available routine method.

52. There are two methods for the determination of exposure to airborne contamination:

(a) the use of representative/area air monitoring data, combined with a knowledge of occupancy of individual workers within each sampling area and an assumed breathing rate. This method is often used in situations where the more significant intakes are associated with well defined work activities; and
(b) the routine use of personal air samplers. This is often used where significant contributions to internal exposure are not linked to identifiable fixed locations.

53. Intakes of radioactive material are normally assessed routinely for workers who are employed in areas that are designated as controlled, specifically in relation to the control of contamination, and in which there are grounds for expecting significant intakes. However, there are difficulties in comparing data on internal doses in different countries because of the different approaches that are used to monitor and interpret the results. Measurements in a routine monitoring programme are often made at predetermined times not necessarily related to a particular intake event, and it is therefore necessary to make some assumptions about the pattern of intakes. Guidance on interpreting the results of measurements of intakes of radionuclides by workers was given in ICRP Publication 54 [I11]. This publication has been replaced, however, by a new document [I1] that uses current biokinetic models and is consistent with ICRP Publication 68 [I15]. In keeping with the ICRP advice, it is usual for the results of *in vivo* and *in vitro* monitoring measurements to be interpreted using the assumption that the intake took place at the mid-point of the interval between monitoring times. Assessment of doses from air sampling data requires knowledge of the physical and chemical properties of the radioactive materials, including the particle size and solubility in biological fluids. The current recommendation of ICRP [I15] is that a default value of 5 µm should be used for the particle size; previously, a value of 1 µm was recommended and may still be in use. A major difficulty in using area air sampling data to assess dose is whether the measurement data can be related to the activity concentration in the breathing zone. There is also the particular difficulty in interpreting area air sampling data when the contamination is due to localized sources or where only a few particles of radioactive material can represent a significant intake.

54. With the techniques currently available, it is generally not possible to obtain the same degree of precision in routine assessments of dose from intakes of radioactive material as is possible with external radiation. The dose assessment falls into three stages:

(a) individual monitoring measurements;
(b) assessment of intake from the measurements; and
(c) assessment of doses from the intake.

The overall uncertainty in the assessed dose will be a combination of the uncertainties in these three stages. A good example of the uncertainties involved and the relative merits of various dose assessment techniques is provided by a study of chronic low-level exposure of workers in nuclear fuel reprocessing [B3]. The study was able to compare assessments of intakes from static air sampling (SAS) and personal air sampling (PAS) and to then compare dose assessments from personal air sampling and biological *in vitro* samples. In the first of these comparisons, the dose assessed by personal air sampling was about an order of magnitude larger than that implied by static air sampling. For the group as a whole, over a seven-year period there was reasonable agreement between the geometric mean cumulative doses (23 mSv for biological sampling and 30 mSv for personal air sampling). However, there was a lack of correlation when viewed at any individual level, with no single identifiable factor to explain the difference. This must cast some doubt on the adequacy of personal air samplers for estimating annual intakes of individual workers at the levels of exposure encountered in operational environments.

55. In practice, there are relatively few occupational situations in which internal exposures to man-made sources of radiation are significant, and significant exposures have generally been decreasing. Exposures may still be significant in a number of situations, however: the handling of large quantities of gaseous and volatile materials such as tritium (e.g. in the operation of heavy-water reactors and in luminizing); reactor fuel fabrication; the handling of plutonium and other transuranic elements (e.g. in the reprocessing of irradiated fuel and in nuclear weapons production); and some nuclear medicine situations. Significant internal exposures to natural radionuclides can occur in the mining and processing of radioactive ores, particularly uranium ores but also some other materials with elevated levels of natural radionuclides (e.g. mineral sands). Significant exposure to radon can also occur in other mines, underground areas such as show caves (e.g. those that are open to tourists), and some aboveground workplaces not normally associated with radiation exposure.

C. DOSE RECORDING AND REPORTING PRACTICES

56. In most countries dose recording and reporting practices are governed by regulations and can be different for various categories of workers depending on their anticipated levels of exposure. Like monitoring practices, they vary from country to country and may significantly affect the reported collective doses. The most important differences arise from the following:

(a) the recording of doses less than the minimum detectable level (MDL);
(b) the measurement technique used, for example, TLD, film, or electronic dosimeter in the case of external radiation exposure;
(c) the assignment of doses to fill missing record periods;
(d) the treatment of unexpectedly high doses;
(e) the subtraction of background radiation doses;
(f) the protocol for determining who in the workforce should be monitored and for whom doses should be recorded in particular categories; and
(g) whether or not internal exposures are included or treated separately.

57. The recording level is the level above which a result is considered to be significant enough to be recorded, lower values being ignored [I12]. Recent advice from ICRP is

that the recording level for individual monitoring should be based on the duration of the monitoring period and an annual effective dose no lower than 1 mSv [I17]. In practice, little use is made of recording levels in individual monitoring for external radiation exposure, and many countries adopt the practice of recording all measured doses above the MDL for the technique used. When doses are determined to be less than the MDL, the value recorded may be zero, some pre-designated level, or the MDL itself. These differences affect the comparability of results. Furthermore, the MDL will vary with the device used. For example, the MDL associated with electronic dosimeters is generally much lower than that for film badges or TLDs. Electronic dosimeters have not been extensively used for the assessment of individual dose for record keeping purposes, but this situation is changing. This could lead to significant differences in the recording of low levels of external exposure. For instance, during the first four months of operation of an electronic dosimetry system at Sizewell B nuclear power plant in the United Kingdom, the monthly collective dose measured by film badges was higher by a factor of 20 than that measured by electronic dosimeters [R1]. It is therefore important to understand the implications of recording levels and different MDLs on the average individual dose and collective dose.

58. When dosimeters are lost or readings are otherwise not available, administrative procedures are then used in assigning doses to individual dose records. These are assumed doses to the workers for the appropriate period for which measurements are not available. A variety of procedures are used in determining the assigned dose. These include the assignment of the appropriate proportion of the annual limit for the period for which the dosimeter was lost; the assignment of the average dose received by the worker in the previous 12 months; and the assignment of the average dose received by co-workers in the same period. Some of these procedures can distort records significantly, particularly if large numbers of dosimeters are lost within a particular occupational group. Where this is the case, direct comparisons with other data may be invalid or, at least, need qualification. A similar situation may arise in the treatment of unexpectedly high measured doses that are considered not to be a true reflection of the actual doses received.

59. The background signal of a dosimeter involves contributions from both the non-radiation-induced signals from the dosimeter and the response of the dosimeter to natural background radiation. This signal is often subtracted from the actual dosimeter reading before recording. In many countries, the practice is to use a single value that takes account of the contributions to the background signal, that from natural background radiation being the average for the country as a whole. Where there are significant variations in the gamma-ray contribution from natural sources, this practice may have some influence on the individual doses that are recorded, particularly where the occupational exposures are similar in magnitude to those from the natural environment.

60. In the past, internal and external exposures were generally recorded separately. Furthermore, there were significant variations in the reporting levels for internal contamination, and this added to the difficulty of compiling meaningful statistical information. There is now increased emphasis on recording the sum of the annual effective dose from external irradiation and the committed effective dose from internal irradiation. Such data will enable more valid comparisons to be made of the radiological impact of different practices. However, comparisons of the more recent data with data for earlier periods will need to be treated with caution. For example, internal exposures in some occupations and industries (fuel fabrication and fuel reprocessing) may have been significant during the periods covered in previous assessments by the Committee but may not have been included in the data. Furthermore, inclusion of internal doses may result in an apparent step increase in the level of exposure received by workers in industries where internal exposure contributes significantly.

61. A major cause of difficulty in comparisons, particularly of average individual and collective doses, is the protocol used for determining who in the workforce is to be monitored and to have data recorded within any particular category. For instance, it is important to know whether the data for nuclear power operations include doses to visitors, administrative staff, and contract workers in addition to the company's employees.

62. In the UNSCEAR 1993 Report [U3], the advantage was noted of reporting data according to an agreed categorization scheme of work and also the difficulty of doing so, particularly in view of the differences in long-established national practices. The categories used by the Committee in this Annex are given in Table 1; there are some differences between this categorization and that used in the UNSCEAR 1993 Report. The main differences are that veterinary practice and educational establishments are now placed in a miscellaneous category, and there is some development of the section on natural radiation. However the approach adopted should still permit broad comparisons to be made with the data in the UNSCEAR 1993 Report. The dose monitoring and recording procedures for occupational exposure obtained from the UNSCEAR Survey of Occupational Radiation Exposures are given in Table 2. The data are not comprehensive for some of the attributes.

63. Any harmonization of the way data are recorded in various countries would help in future surveys. The European Union has an ongoing project, European Study of Occupational Exposure (ESOREX) [F3], to compare the administrative systems of the member states that are used for registering individual occupational exposure, to identify differences, and to analyse the possibility of harmonization within Europe. The project has also been extended to cover central and east European countries [F4].

D. CHARACTERISTICS OF DOSE DISTRIBUTION

64. Dose distributions are the result of many constraints imposed by the nature of the work, by management, by the workers, and by legislation. In some job categories it may be unnecessary for workers ever to receive more than very low doses, whereas in other jobs workers may have to be exposed to high doses fairly routinely. Management controls act as feedback mechanisms, especially when individual doses approach the annual dose limit, or some proportion of it, in a shorter period of time.

65. The Committee is principally interested in comparing dose distributions and in evaluating trends. For these purposes, it identified three characteristics of dose distributions as being particularly useful:

(a) the average annual effective dose (i.e. the sum of the annual dose from external irradiation plus the committed dose from intakes in that year), $\bar{E}$;
(b) the annual collective effective dose, S (referred to as M in some earlier UNSCEAR reports), which is related to the impact of the practice; and
(c) the ratio, SR_E, of the annual collective effective dose delivered at annual individual doses exceeding E mSv to the total collective dose. SR (referred to as MR in some earlier UNSCEAR reports) provides an indication of the fraction of the collective dose received by workers exposed to higher levels of individual dose. This ratio is termed the collective dose distribution ratio.

66. Another ratio, NR_E, of the number of workers receiving annual individual doses exceeding E mSv to the total monitored or exposed workforce, is reported in many occupational exposure statistics, often when the ratio SR_E is not provided. The more frequent reporting of the ratio NR_E is probably due to the ease with which it can be estimated. In the past, the Committee was somewhat concerned because of the ratio's potential sensitivity to how the size of the workforce is defined (those monitored, those measurably exposed, etc.); comparisons of values of this ratio for different occupations and in different countries would, in general, require some qualification. The ratio SR_E, on the other hand, is relatively insensitive to this parameter and is therefore a better means of affording fair comparisons between exposures arising in different industries or practices. Notwithstanding the limitations of the ratio NR_E, it is included in the characteristics reported by the Committee. This reflects its potential for use in more limited circumstances (e.g. when analysing trends with time in a given workforce or making comparisons between workforces that have been defined in comparable ways). The ratio SR_E, however, remains the most appropriate basis for comparing data generally.

67. 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, $\bar{E}$, 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. 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 exceeding E mSv.

68. The total number of workers, N, warrants further comment, as it has implications for the various quantities estimated. Depending on the nature of the data reported and subject to the evaluation (or the topic of interest), the number of workers may be those monitored, those classified, those measurably exposed, the total workforce, or some subset thereof. These quantities, therefore, 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. These aspects were discussed in Section I.C, where the implications of different monitoring and reporting practices for the assessed average individual and collective doses were identified. In this Annex, consideration is, to the extent practicable, limited to the estimation of the above quantities for the monitored and measurably exposed workforces; however, lack of uniformity between employers and countries in determining who should be monitored and/or what constitutes measurably exposed means that even these comparisons between ostensibly the same quantities are less rigorous than might appear. Where necessary, quantities estimated for a subset of the workforce (e.g. those measurably exposed) can be transformed to apply to the whole workforce; methods of achieving this, based on characteristics of the dose distributions, are discussed below.

69. In summary, the following characteristics of dose distributions will be considered by the Committee in this assessment of occupational exposures:

(a) the average annual effective dose (i.e. the sum of the annual dose from external radiation and the committed dose from intakes in that year), $\bar{E}$;

(b) the annual collective effective dose (i.e. the sum of the annual collective dose from external irradiation and the committed collective dose from intakes in that year), S;

(c) the collective dose distribution ratio, SR_E, for values of E of 15, 10, 5, and 1 mSv; and

(d) the individual dose distribution ratio, NR_E, for values of E of 15, 10, 5, and 1 mSv.

E. ESTIMATION OF WORLDWIDE EXPOSURES

70. Inevitably, the data provided in response to the UNSCEAR Survey of Occupational Radiation Exposures were insufficient for estimating worldwide levels of dose. Procedures were therefore developed by the Committee to derive 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.

71. 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. The degree of extrapolation from reported to worldwide doses is, therefore, less, and this extrapolation can be carried out with greater reliability than for other occupational categories. Moreover, worldwide statistics are generally available on 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, from a given stage of the nuclear fuel cycle (e.g. uranium mining, fuel fabrication, or reactor operation) is estimated to be the total of annual collective effective doses from reporting countries times the reciprocal of the fraction, f, of 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 from country c and n is the number of countries for which occupational exposure data have been reported. The fraction of 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 country c and in the world, w, respectively.

72. The annual number of monitored workers worldwide, N_w, 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 annually. Values of these quantities have been averaged over five-year periods, and the average annual values are reported in this Annex.

73. For occupational exposures to radiation from practices other than operations of the nuclear fuel cycle, statistics are not so readily available on the worldwide level of the practices or their distribution among countries. In these cases a simpler and, inevitably, less reliable method of extrapolation has to be used. A variety of approaches are possible (e.g. scaling by size of population, by employment in industrial or medical professions, or by some measure of industrial output). In the end, it seemed to be most practical and reasonable to extrapolate on the basis of GDP [U14]. Several considerations influence the choice of this quantity in preference to others, notably the availability of reliable worldwide statistics on GDPs and their potential for general application; the latter is a consequence of the expectation that GDP is reasonably correlated with both the level of industrial activity and medical care in a country, characteristics unlikely to be reflected in any other single quantity. To make the extrapolation more reliable, it is applied not globally but separately over particular geographic or economic regions, followed by summation over these regions. This results in extrapolations of available data within groups of countries with broadly similar levels of economic activity and allows for general geographical comparisons.

74. The worldwide annual collective effective dose for other uses of radiation, is estimated as

$$S_w = \sum_{r=1}^{m} S_r$$

where

$$S_r = \frac{1}{g_r} \sum_{c=1}^{n_r} S_c$$

where S_r is the annual collective effective dose in geographic or economic region r, n_r is the number of countries in region r for which occupational exposure data have been reported, m is the number of regions, and g_r is the fraction of GDP of region r, represented by those countries for which occupational exposure data are available and is given by

$$g_r = \sum_{c=1}^{n_r} G_c \;/\; G_r$$

where G_c and G_r are the GDPs of country c and region r, respectively.

75. The above equations are applied to estimate collective doses for those regions for which occupational exposure

data are available for at least one country within the region. For those regions for which no data for any country were reported, a modified approach for estimating regional collective dose is adopted:

$$S_r = G_r \sum_{c=1}^{n} S_c \; / \sum_{c=1}^{n} G_c$$

76. The annual number of monitored workers worldwide, N_w, is estimated by the same procedure. The worldwide distribution ratios are estimated as for operations of the nuclear fuel cycle, but the averaging is performed on a regional basis before summing over all regions. The number of measurably exposed workers worldwide, M_w, is estimated in a similar manner.

II. THE NUCLEAR FUEL CYCLE

77. 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 [U8], 1977 [U7], 1982 [U6], 1988 [U4], and 1993 [U3] Reports, with comprehensive treatment in the UNSCEAR 1977 and 1982 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. As 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 from waste disposal are not expected to significantly increase the sum of the doses from the other stages in the fuel cycle. For similar reasons, no attempt is made to estimate occupational exposures during the decommissioning of nuclear installations, although this will become an increasingly important stage.

78. Each stage in the fuel cycle involves different types of workers and work activities. In some cases, e.g. for reactor operation, the data are well segregated, while in others the available data span several activities, e.g. uranium mining and uranium 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 Survey of Occupational Radiation Exposures but also from other sources, particularly the Information System on Occupational Exposure of the OECD/NEA [O4, O5].

79. For each stage of the fuel cycle estimates are made of the magnitude and temporal trends in the annual collective and average individual effective doses, the numbers of monitored workers, and the distribution ratios. The collective doses are also expressed in normalized terms, that is, 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, namely, the amounts of mined uranium, the separative work during enrichment, and the amount of fuel required to generate a unit of electrical energy in various reactor types, are given in Annex C, "*Exposures to the public from man-made sources of radiation*". 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 per reactor and per unit electrical energy generated.

80. 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 fuel fabricated or reprocessed, corresponding to a unit of energy subsequently generated in the reactor), which is the output of the nuclear power industry. This form of normalization is both valid and useful when treating data accumulated 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 averaged over five-year periods.

81. 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 Survey of Occupational Radiation Exposures are summarized in Table 2. The potential for such differences to compromise or invalidate comparisons between data is discussed in Section I.A.3. The reported collective doses and the collective dose distribution ratios are largely insensitive to the differences identified in Table 2, 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 decisions and practice on who in a workforce is to be monitored. Differences in these areas could not be discerned from responses to the UNSCEAR Survey of Occupational Radiation Exposures, so

they cannot be discerned from Table 2. 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 between reported data; to the extent practicable, where such differences are likely to be important they are identified.

A. URANIUM MINING AND MILLING

82. Uranium is used for military, commercial, and research purposes. It is widely distributed in the earth's crust, and mining is undertaken in over 30 countries [O3]. Commercial uranium use is primarily determined by the fuel consumption in nuclear power reactors and nuclear research reactors and by the inventory requirements of the fuel cycle. Uranium requirements for power reactors continue to increase steadily, while the requirements for research reactors remain modest by comparison. The annual production of uranium in various countries in the years 1990–1997 is given in Annex C, "*Exposures to the public from man-made sources of radiation*", and more detailed information can be found in an OECD/NEA publication [O3].

83. 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 at a location relatively near the mine. The milling process involves the crushing and grinding of raw ores, followed by chemical leaching, separation of uranium from the leachate, precipitation of yellowcake [K4], and drying and packaging of the final product for shipment. In response to the declining price of uranium, the emphasis in recent years has been on lower-cost methods for extracting uranium [O3]. The percentage of conventional underground mining was reduced from about 55% to about 45% from 1990 to 1992. The lower-cost methods are open-pit mining, *in situ* leaching, and by-product production (e.g. from the mining of other minerals such as gold). The percentage from conventional open-pit mining increased during this period, from 38% to 44%; that from *in situ* leaching from 5.7% to 9.1%; and that from by-product production from 1.1% to 2.2%. In 1992, there were 55 operating uranium mines in the world in over 21 countries, with 32% of the production coming from Canada alone. About 84% of the world's production came from only 12 countries: Australia, Canada, France, Kazakhstan, Kyrgyzstan, Namibia, Niger, the Russian Federation, South Africa, Tadjikistan, Uzbekistan, and the United States [G2] (see Table 28 of Annex C, "*Exposures to the public from man-made sources of radiation*", for annual production of uranium in other years between 1990 and 1997).

84. The mining and milling of uranium ores can lead to both internal and external exposures of workers. Internal exposure may arise from the inhalation of radon gas and its decay products and radionuclides in ore dust. The extent of internal exposure will depend on many things, including 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 from this source would be expected in the milling of the ores and production of yellowcake.

85. With the emphasis on low-cost uranium production, new projects are expected to focus on high-grade unconformity and sandstone-type deposits. These may be amenable to *in situ* leaching techniques, but where underground mining is used, exposures of workers are likely to continue to be of concern. In future surveys there will be a need to consider the exposures that arise during the rehabilitation of old mining operations. For example in Germany, where uranium mining is no longer undertaken, annual exposures to workers due to the removal of uranium mining residues are estimated for 1995 to be distributed as follows: 1–6 mSv, 1,250 workers; 6–20 mSv, 230 workers; and >20 mSv, no workers [S2]. The exposures result from external radiation, inhalation of radioactive dust particles, and inhalation of radon progeny.

86. Exposure data for mining and milling of uranium ores from the UNSCEAR Survey of Occupational Radiation Exposures for 1990–1994 are given in Tables 3 and 4, respectively; and trends for the four periods from 1975 are given in Figure II. The questionnaire asked respondents to use a conversion factor for exposure to radon decay products of 5 mSv per WLM, the value recommended by ICRP [I12].

87. Over the three previous five-year periods the average annual amounts of uranium mined worldwide were 52, 64, and 59 kt, a reasonably constant level of production, with by far the largest part mined underground. As has already been mentioned, there has more recently been a move away from underground mining and a reduction in the amount mined. For the 1990–1994 period, the average annual amount mined was 39 kt, a reduction of about one third. The year-on-year figures showed a steady downward trend, from 49.5 kt in 1990 to 31.6 kt in 1994. During this period a number of countries, including Bulgaria, Germany, and Slovenia, reported that mining operations had ceased, although some exposures continued from measures to treat the closed-down mining operations. These trends would be expected to affect both the magnitude of the collective doses and the dose profiles, and indeed they do so.

88. The data set for 1990–1994 is smaller than for the preceding period, 1985–1989, with data from 10 countries as

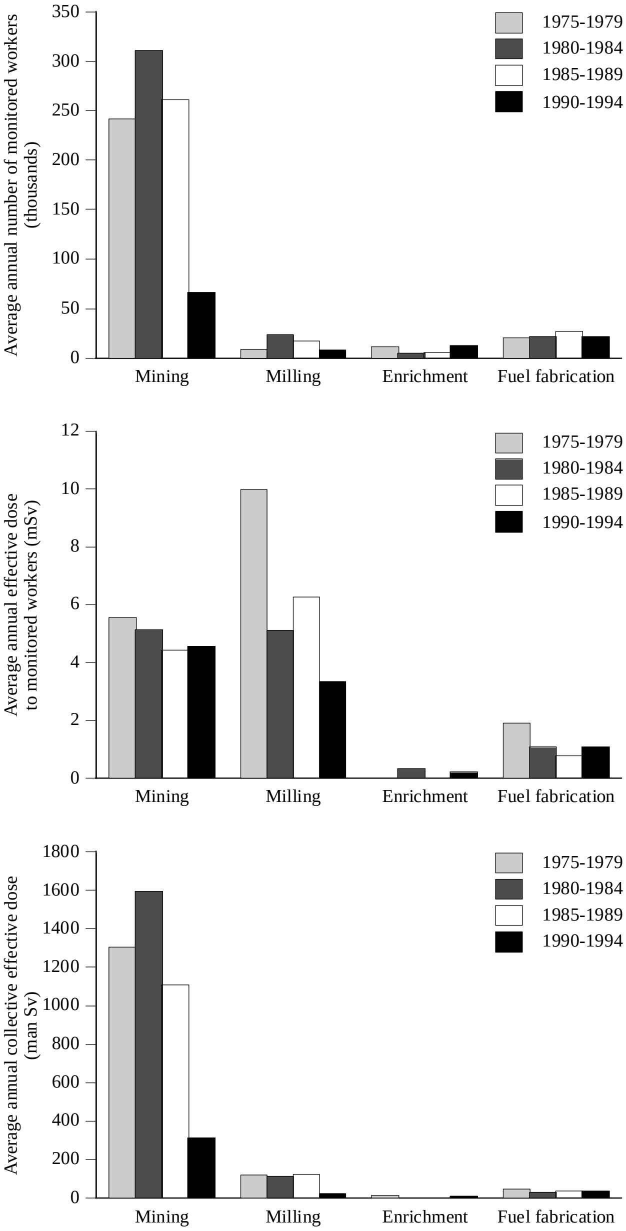

Figure II. Trends in numbers of monitored workers, doses to workers, and collective doses for mining, milling, enrichment and fuel fabrication.

opposed to 14 countries, respectively. The 1985–1989 data were dominated by underground mining data from South Africa, which accounted for some 70% (82,000) of the total reported monitored workers (114,000) and 55% (278 man Sv) of the reported collective dose (507 man Sv). China also made an important contribution to the 1985–1989 data, with a reported collective dose of 114 man Sv, some 22% of the total reported. The lack of data for 1990–1994 from South Africa and China (and, to a lesser extent, from India and the United States) distorts any extrapolation to arrive at a world figure. For the earlier periods the extrapolation for the number of monitored workers and collective dose worldwide was based on the ratio between the total amount of ore produced by the reporting countries and total world production. Employing the same approach to the 1990–1994 period would give a worldwide monitored population of 28,000 and an average annual collective effective dose of 140 man Sv. Both of these estimates are an order of magnitude less than for 1985–1989. The Committee regarded this as a significant underestimate and has instead chosen to make estimates for those countries that had not reported for 1990–1994 but that did report for 1985–1989, before extrapolating on the basis of worldwide production of uranium ore. This approach has the benefit of ensuring that major contributors such as South Africa and China are more adequately accounted for. The estimates for these countries (shown in square brackets in Table 3) are based on the average trends for countries reporting for both 1985–1989 and 1990–1994 and take into account the best estimates of uranium ore production. On this basis, the average annual number of monitored workers worldwide fell from 260,000 in 1985–1989 to 69,000 in 1990–1994. For the previous two periods the numbers had been 240,000 and 310,000. This reduction by a factor of 3 or 4 is also seen in the values for average annual collective effective doses. For the three previous periods the worldwide estimates were 1,300, 1,600 and 1,100 man Sv, but for 1990–1994 the value was 310 man Sv. Similarly, the average collective dose per unit of uranium extracted had been 26, 23, and 20 man Sv per kt for the three previous periods and was down to 7.9 man Sv per kt for 1990–1994; the corresponding values for average collective dose per unit energy were 5.7, 5.5, and 4.3 man Sv per GWa, falling to 1.7 man Sv per GWa for 1990–1994 (see Figure III). However, the estimated average annual effective dose, 4.5 mSv, was marginally higher than for the immediately preceding period, when it was 4.4 mSv. With the doses from underground mining dominating the collective dose and the known difficulties in reducing individual doses, the data would be consistent with a worldwide reduction in underground mining activity coupled with more efficient mining operations.

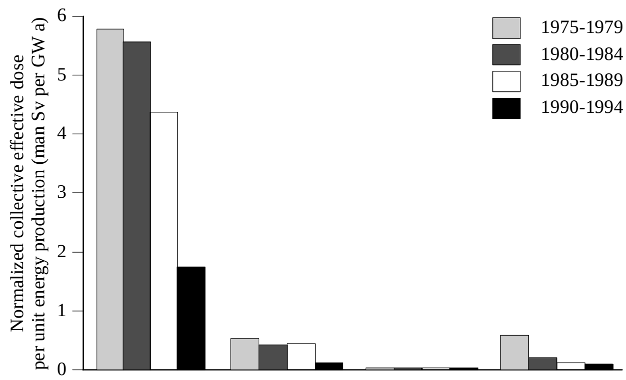

Figure III. Normalized collective effective dose per unit energy production for mining, milling, enrichment and fuel fabrication.

89. Data on exposure to workers from uranium milling were provided from only two countries, Australia and Canada, and are given in Table 4. In line with their reductions in mining, both countries show significant reductions in the number of monitored workers and the collective dose. It is difficult to extrapolate worldwide from these data, but crude estimates can be made. As in previous

UNSCEAR reports it is assumed that the amount of uranium milled is equal to the amount mined. The combined data for the two countries reporting show a reduction by a factor of about 4 in the average annual collective dose and about a factor of 2 in the number of monitored workers relative to 1985–1989. These factors are in line with the trends for uranium mining, and it would seem appropriate to apply them to derive worldwide estimates for 1990–1994. Doing so leads to worldwide estimates for average annual monitored workers of 6,000 compared with 12,000, 23,000, and 18,000 in each of the three previous periods; to an average annual collective effective dose of 20 man Sv compared with 124, 117, and 116 man Sv in each of the three previous periods; and to an average annual effective dose of 3.3 mSv compared with 10.1, 5.1, and 6.3 mSv in each of the three previous periods.

B. URANIUM ENRICHMENT AND CONVERSION

90. 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. In reactors that use fuel slightly enriched in ^{235}U (generally about 3%; natural uranium contains about 0.7% ^{235}U), uranium from the milling process must be enriched before fuel fabrication. Thus, the U_3O_8 from the milling process is converted to UO_2 by a reduction reaction with H_2. The UO_2 is then converted to UF_4 by the addition of hydrofluoric acid (HF), and then to UF_6 using fluorine (F_2). This gaseous product, UF_6, is then enriched in ^{235}U. Most of this was done by the gaseous diffusion process, but increasingly, gaseous centrifuge techniques are being used. Once the enrichment process has been completed, the UF_6 gas is reconverted into UO_2 for fuel fabrication. Occupational exposures occur during both the conversion and enrichment stages, with, in general, external radiation exposure being more important than internal radiation exposure. Workers may, however, be exposed to internal radiation, particularly during maintenance work or in the event of leaks.

91. During 1990–1994 most enrichment services came from five suppliers: Department of Energy (United States), Eurodif (France), Techsnabexport (Russian Federation), Urenco (Germany, Netherlands and United Kingdom) and China. (Entities in those same countries, plus Canada, offered services for the conversion process that precedes enrichment.) The enrichment capacity of these and a few other small producers has been estimated at between 32 and 35 million separative work units (MSWu) per annum during 1990–1994 compared with demand of between 23 and 27 MSWu [O8, O9]. Exposure data for 1990–1994 are given for Canada, France, Japan, the Netherlands, South Africa, the United Kingdom, and the United States in Table 5. With three exceptions the data are for enrichment by the diffusion process; the exceptions are South Africa, where the helicon enrichment process has been used, and the United Kingdom and Japan, where centrifuge enrichment is used. It is not possible to compare the two time periods because data from the United States dominated the 1985–1989 set, and the 1990–1994 set reflects an important contribution from Canada as well as a significant increase in the South African data. Based on reported data, the annual collective effective dose increased from 0.43 man Sv to 0.79 man Sv, and the resultant average dose per monitored worker increased from 0.08 mSv to 0.14 mSv. However, it should be noted that the values for 1985–1989 were somewhat lower than for earlier periods.

92. Sums or averages of reported data are given in Table 5; however, because data on the separative work used in uranium enrichment are incomplete, an extrapolation based on size of the practice to estimate worldwide doses cannot be made. The alternative extrapolation, based on GDP, would also be inappropriate in this case, because enrichment is carried out in only a few countries. Accordingly, worldwide doses can be estimated only roughly.

93. The data for the five-year periods before 1990–1994 were dominated by the data from the United States, which accounted for some 80% of the collective dose estimates. Although the United States did not report data for 1990–1994, the totals increased. The average annual number of monitored workers increased from 5,000 to 12,600 between the last two reporting periods, and the average annual collective dose increased from 0.43 to 1.28 man Sv. The average annual effective dose to monitored workers was low, 0.10 mSv, in 1990–1994 and comparable to the value of 0.08 mSv for the preceding period. The absence of data from the Russian Federation and China would suggest that these figures are underestimates; but probably only by a factor of 2 or 3. Even taking this into account, the individual and collective doses from enrichment are small. Consequently, despite the major uncertainties in estimating worldwide exposures from this source, it would be appropriate to accept (as was done in the UNSCEAR 1993 Report) the reported data as being indicative of the worldwide figure. This will have little impact on the reliability of the estimated exposure from the whole of the nuclear fuel cycle.

C. FUEL FABRICATION

94. 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 a few percent of ^{235}U); the main exceptions are the gas-cooled Magnox reactors and the heavy-water-cooled and -moderated reactors, which use natural uranium. Some older research reactors use highly enriched uranium (up to 98%); however, for security reasons this material is used less and less. The four types of uranium fuel are unenriched uranium metal fuel, used in Magnox reactors; low enriched uranium oxide fuel, used in advanced gas-cooled, graphite-moderated reactors (AGRs) and in light-water-moderated and -cooled reactors (LWRs); unenriched oxide fuel is generally used in heavy-water-

cooled and -moderated reactors (HWRs); and mixed uranium/plutonium oxide (MOX) fuel used in LWRs and in fast breeder reactors (FBRs). The principal source of exposure during fuel fabrication is uranium (after milling, enrichment, and conversion, most decay products have been removed). This can lead to external exposure from gamma rays and intake of airborne activity.

95. The reports for the first period (1977–1979) in the UNSCEAR 1982 Report [U6] and for the second period (1980–1984) in the UNSCEAR 1988 Report [U4] considered exposures from fuel fabrication and uranium enrichment as one category. The UNSCEAR 1993 Report [U3] (for 1985–1989) considered the two categories separately and also carried out a detailed analysis by fuel type. In devising the UNSCEAR Survey of Occupational Radiation Exposures for 1990–1994, it was concluded that for this review a single category for fuel fabrication, separate from fuel enrichment and conversion, would be appropriate. The data from the UNSCEAR Survey of Occupational Radiation Exposures are given in Table 6.

96. The worldwide production of fuel increased steadily over the four five-year periods being 3.6, 6.1, 9.6 and 11.3 kt from first to last, as did the corresponding equivalent energy figures, 60, 100, 180, and 210 GWa. In all periods the production of fuel for LWRs dominates. Worldwide estimates of the average annual collective effective dose and the average annual number of monitored (and measurably exposed) workers have been obtained by scaling the sum of the reported data by the ratio of the fuel fabricated worldwide to that fabricated in those countries reporting data. A number of approximations had to be made in this extrapolation process owing to the absence of adequate data on the production of fuel worldwide and in some major producing countries. Annual fuel production in these cases was assumed to be equal to the production that would have been required for the generation of electrical energy by the reactors in that country. This method of extrapolation is the same as that used in the UNSCEAR 1993 Report [U3]. The data were taken from OECD and IAEA reviews [I2, I21, O8, O9], and the Committee's estimates are given in brackets in Table 6. The fact that some countries export or import fuel inevitably introduces a degree of uncertainty into the figures, so comparisons between periods and between countries should be treated with caution.

97. The average annual number of monitored workers has been reasonably constant over the four 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 for 1990–1994 was approximately 11,000, about half the number of monitored workers. This is the first period for which a reasonable estimate has been possible. The estimated average annual collective dose showed a decline, from 36 to 21 man Sv, between the first two five-year periods but subsequently varied little, with the value for 1990–1994 being approximately 22 man Sv. The average annual effective dose to monitored workers showed an initial decline from 1.8 mSv to 1.0 mSv between the first two periods, and the value for 1990–1994, 1.03 mSv, is very similar to that for 1980–1984. The value of 0.78 mSv for 1985–1989 reflects the estimate of the number of monitored workers, which may have been an overestimate. While the collective dose has remained reasonably constant, it has done so against a background of increasing fuel fabrication; consequently, the normalized collective dose per kt of fuel and per unit energy has fallen, from 10.0 to 1.9 man Sv per kt fuel and from 0.59 to 0.10 man Sv per GWa.

D. REACTOR OPERATION

98. 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), 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) make only a minor contribution to energy production at the present time. From 1990 to 1994, the number of operating reactors remained relatively stable, increasing slightly from 413 to 432 by the end of the period, with an annual average of 421. A listing of nuclear reactors in operation during 1990–1997, the installed capacities, and electrical energy generated is given in Annex C, "*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 GWe (net gigawatts electric) [I2]. They now supply about 17% of the total electrical energy generated in the world and account for about 6% of the world's total energy consumption.

99. In addition to data acquired in the UNSCEAR Survey of Occupational Radiation Exposures, data on exposures of workers at nuclear power reactors are also available from the database of OECD/NEA [O4, O5]. This database, known as the Information System on Occupational Exposure (ISOE), was begun in 1990 and involves a growing number of countries, including those from outside OECD, whose data are provided through the IAEA. The programme has been designed to provide an exchange of information on techniques and experience for assessing exposure trends, comparison of practices and results, and as low as reasonably achievable (ALARA) analyses. The ISOE data on occupational exposures at nuclear power reactors for 1990–1994 [L5] and data from the UNSCEAR Survey of Occupational Radiation Exposures for the various types of reactors are given in Table 7.

100. 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, GCRs (which include older Magnox reactors as well as a newer generation of reactors, advanced gas-cooled reactors (AGRs), HWRs, and LWGRs. Within each category, much diversity of design and diversity in the refuelling schedule can be seen, which may contribute to differences in occupational exposures. 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 elaborated upon in this Section.

101. Over 300 reactors (three quarters of the total number) presently operating in the world are light-water reactors (LWRs), either PWRs or BWRs. Of these, the PWRs are more common (70% of LWRs). HWRs have been developed particularly in Canada and are also used in Argentina, India, and the Republic of Korea. GCRs have been used particularly in the United Kingdom. LWGRs have been developed and used in the countries of the former USSR.

102. The type of reactor is just one determinant of the doses received by workers at reactors. 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 at the reactor. 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 receive some additional external exposure caused by ^{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 from tritium.

103. Throughout the world, occupational exposures at commercial nuclear power plants have been steadily decreasing over the past decade, and this trend is reflected in data for 1990–1994. Regulatory pressures, particularly after the issuance of ICRP Publication 60 [I12] in 1991, technological advances, improved plant designs, installation of plant upgrades, improved water chemistry and improved plant operational procedures and training, and the involvement of staff in the control of their own doses have all contributed to this decreasing trend. In Europe, the European ALARA Newsletter is a good example of the way in which information on reducing individual and collective doses can be disseminated among both operators and regulators. A newsletter with a similar objective had been put out for many years by the Brookhaven National Laboratory in the United States. The newsletters may also contain assessed data on occupational exposures.

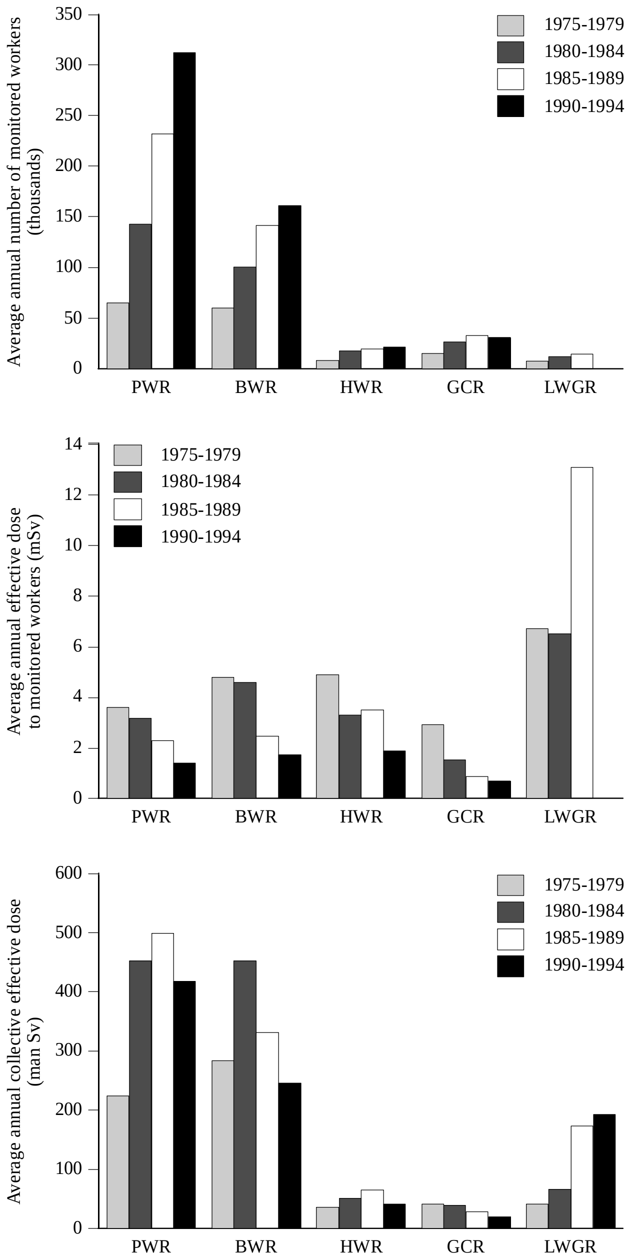

Figure IV. Trends in numbers of mointored workers, doses to workers, and collective doses for reactor operation.

104. Data on occupational exposures at reactors of each type are detailed by country in Table 7 and a worldwide summary by reactor type is given in Table 8. Worldwide levels of exposure have been estimated from reported data; the extrapolations are based on the total energy generated in countries reporting data. Very little extrapolation was needed, as the reported data were substantially complete (about 85% for PWRs, 95% for BWRs, 80% for HWRs, 100% for GCRs, and 60% for LWGRs). The annual data reported in response to the UNSCEAR Survey of Occupational Radiation Exposures have been averaged over five-year periods, and Figures IV and V illustrate some of the trends. Previous UNSCEAR reports treated fast breeder reactors (FBRs) and high-temperature graphite reactors (HTGRs) separately. No

data were provided on these in the UNSCEAR Survey of Occupational Radiation Exposures, and in the main these types of facilities are no longer operational. The UNSCEAR 1993 and 1988 Reports [U3, U4] concluded that they make a negligible contribution to occupational exposure, so they are not considered further.

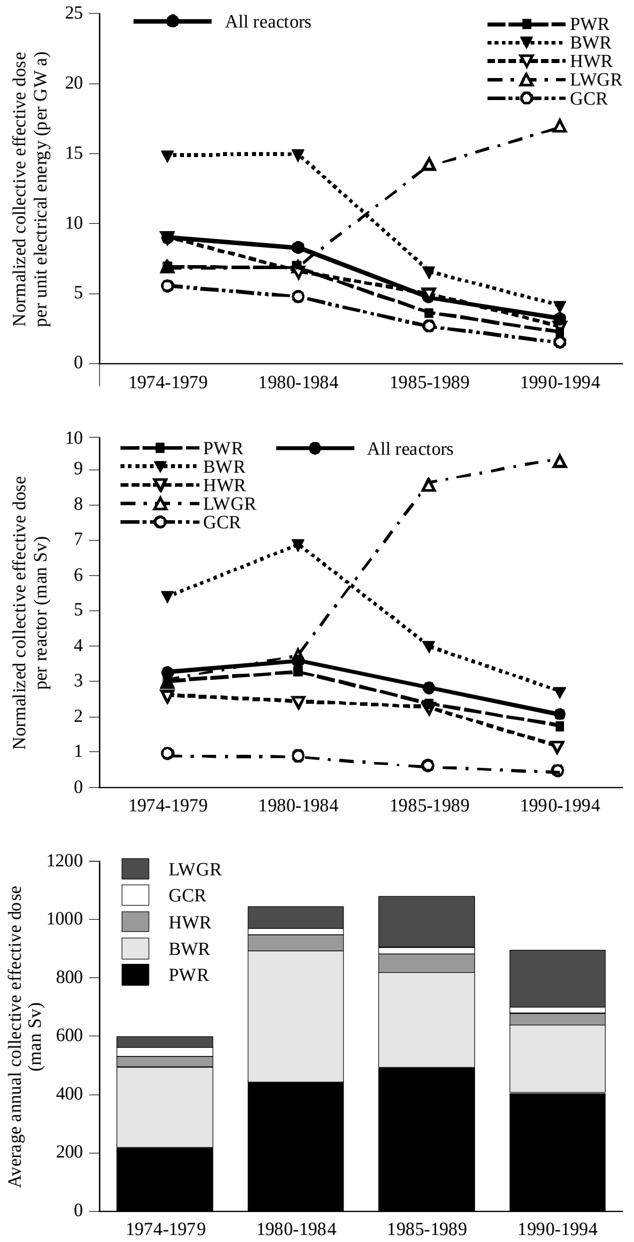

Figure V. Trends in collective effective dose for reactor operation and normalized collective effective dose per reactor and per unit electrical energy.

105. The UNSCEAR 1993 Report [U3] identified the need for more data on measurably exposed workers, as this provides a better basis for comparisons of average doses to individuals than is possible using the monitored worker data. The UNSCEAR Survey of Occupational Radiation Exposures shown in Table 7 now provides good data on measurably exposed workers for PWRs, BWRs, and HWRs. 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) [H2].

106. There remain some difficulties in interpreting and ensuring fair comparisons between the various statistics. These difficulties were discussed in general terms in Section I.A, where a number of cautionary remarks were made. Three more specific observations need to be made in the present context. First, differences exist in the protocols adopted in various countries regarding the fraction of the workforce that is included when evaluating average annual individual doses; in some cases, only measurably exposed individuals are included, whereas generally the whole of the monitored workforce is taken into account. To the extent practicable, a clear distinction is maintained throughout this Annex between the average individual doses evaluated in the different ways. The use of different protocols for determining who in the workforce should be monitored is, however, a further confounding factor. Particular care must therefore be exercised when comparing average individual doses to ensure that the comparisons are made on equal grounds. These differences do not, however, materially affect the estimation or the comparison of collective doses, at least not within the inherent uncertainties associated with their evaluation.

107. Secondly, the procedures for the recording and inclusion of doses received by transient or contract workers may differ from utility to utility and country to country, and this may influence the respective statistics in different ways. In some cases, transient workers may appear in the annual statistics for a given reactor several times in one year (whereas they should appear once only, with the summed dose being recorded); if appropriate corrections are not made, then statistics so compiled will inevitably overestimate the size of the exposed workforce and underestimate the average individual dose and also the fractions of the workforce and the collective dose arising from individual doses greater than the prescribed levels. This will only be important where extensive use is made of transient workers.

108. Thirdly, countries differ in how they report 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; some report data for utility employees only, whereas others present the collective dose for the total workforce but individual doses for the utility workers only. Where necessary and practicable, the reported data have been adjusted to enable them to be fairly compared with other data; these adjustments are indicated in the respective Tables.

1. Light-water reactors

109. LWRs comprise a majority (about 60%) of the installed nuclear generating capacity. About 70% of them are PWRs and about 30% are BWRs. About 33% of the

LWRs are installed in the United States and about 18% in France, with the remainder distributed among some 20 countries. Experience has shown significant differences between occupational exposures at PWRs and those at BWRs. Each type is therefore considered separately.

(a) PWRs

110. External gamma radiation is the main source of exposure in PWRs. Since there is in general only a small contribution from internal exposure, it 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 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 associated with significant dose is the replacement of steam generators. Data on the collective doses associated with this operation have been collected by OECD [O5] and are given in Table 9.

111. The average worldwide number of PWRs increased from 78 in 1975–1979 to 242 in 1990–1994. The corresponding increase in average annual energy generated has been somewhat greater, from 27 to 149 GWa. The number of monitored workers in PWRs increased from about 60,000 to 310,000 (see Figure IV). Between the first two periods the annual average 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, but the fourth period has seen a reduction to 415 man Sv. To see the underlying trend in the efficiency of protection measures from both design and operational procedures it is more instructive to look at the normalized collective dose. Per reactor this increased from 2.8 to 3.3 man Sv over the first two periods but has since dropped, through 2.3 to 1.7 man Sv per reactor. The corresponding values for collective effective dose per unit energy generated (man Sv $(GW\,a)^{-1}$) are (in chronological order) 8.1, 8.0, 4.3, and 2.8, a substantial decrease.

112. The average annual effective dose to monitored workers over the five-year periods has consistently fallen, from 3.5 to 3.1 to 2.2 to 1.3 mSv, an almost threefold reduction overall. For the first time a worldwide estimate of average annual effective dose to measurably exposed workers has been possible; the value of 2.7 is higher by a factor of about 2 than that for monitored workers. The dose distribution data also parallels the downward trend in doses, with both NR_{15} and SR_{15} consistently dropping; the values for 1990–1994 are <0.01 and 0.07, respectively.

113. There is considerable variation about the worldwide average values in both the trends and 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 reports [O2, O3, O4, O5].

(b) BWRs

114. External irradiation 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 number of BWRs are located in the United States and Japan.

115. Worldwide, the average number of BWRs increased from about 51 in 1975–1979 to about 90 in 1990–1994; the corresponding increase in the average annual energy generated worldwide was somewhat greater, from about 15 to 50 GWa. On average, 40% of this energy was generated by BWRs in the United States and 25% of it by BWRs in Japan. The number of monitored workers in BWRs worldwide increased from about 60,000 to about 160,000 over the period (Figure IV). 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. 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 2.7 man Sv in the last two periods. The corresponding values normal-ized to the energy generated, man Sv $(GW\,a)^{-1}$, were 18, 18, 7.9, and 4.8. Both parameters indicate significant reductions over the four five-year periods.

116. The average annual effective dose to monitored workers over the five-year periods has consistently fallen: 4.7, 4.5, 2.4, and 1.6 mSv. As with PWRs, there has been an almost threefold reduction overall. The worldwide average annual effective dose to measurably exposed workers, 2.7 mSv, is about 70% 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 above 15 mSv having been 0.13 in 1990–1994.

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

2. Heavy-water reactors

118. HWRs are used in several countries but most extensively in Canada, where the CANDU reactor was developed and has since been exported to a number of

countries. The main source of occupational exposure in these reactors is, in general, external irradiation, mainly from activation products in the coolant and coolant circuits. As in LWRs, most of the exposures arise during maintenance activities. Internal exposure, however, can also be a significant component of exposure, principally from intakes of tritium produced by activation of the heavy-water moderator.

119. The worldwide average number of HWRs increased from 12 in 1975–1979 to 31 in 1990–1994; the corresponding increase in the average annual energy generated worldwide was somewhat greater, from about 3 to 12 GWa. On average, 80% of this energy was generated by HWRs in Canada. The number of monitored workers in HWRs worldwide increased from about 7,000 to about 20,000 over the 20-year period, as shown in Figure IV. The average annual collective effective dose increased, from about 30 man Sv in the first five-year period to about 45 man Sv in the second period and 60 man Sv in the third; in the fourth period, however, it decreased significantly, to 20 man Sv. Internal exposure made a significant contribution to the overall dose; the contribution varied from year to year and between countries but on average was 30%, varying typically from 15% to 50%. Over the first three periods, the normalized average annual collective effective dose per reactor dropped slightly (2.6 to 2.3 man Sv), but the fourth period has seen a twofold reduction, to 1.1 man Sv per reactor. The corresponding values normalized to the energy generated, man Sv $(GW\ a)^{-1}$, were 11, 8.0, 6.2, and 3.0.

120. The average annual effective dose to monitored workers over the first two periods fell from 4.8 to 3.2 mSv but was then stagnant for the third period. However the last period, 1990–1994, saw a significant reduction, to 1.7 mSv, again a decrease by a factor of about 2. The data are dominated by the Canadian data and show a consistent downward trend. However there are significant variations around the worldwide averages, most notably for Argentina, where for the first three periods the average annual effective dose to monitored workers exceeded 10 mSv. For the latest period it fell to 8.2 mSv (compared with 1.1 mSv for Canada). These differences are also very apparent in the distribution ratios: in Argentina 65% of the collective dose comes from individual annual doses in excess of 15 mSv, while in Canada the corresponding figure is 11%.

3. Gas-cooled reactors

121. There are two main types of GCRs: Magnox reactors, including those with steel pressure vessels and those with prestressed concrete pressure vessels, and advanced gas-cooled reactors (AGRs). Another type, HTGRs, reported on previously [U6], 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, both in terms of their installed capacity and energy generated, became more important. The relative importance of AGRs will increase as Magnox reactors are decommissioned.

122. The UNSCEAR 1993 Report [U3] investigated the differences between the Magnox reactors and AGRs. These arise mainly from the use of concrete (as opposed to steel) pressure vessels in the AGRs (and later Magnox reactors) and the increased shielding they provide against external radiation, the dominant source of occupational exposure. That Report identified significant differences between the various types, with the average annual effective dose in first-generation Magnox steel-pressure-vessel reactors remaining uniform at about 8 mSv whereas the values for Magnox concrete-pressure-vessel reactors and AGRs were less than 0.2 mSv. During the current reporting period, 1990–1994, significant dose reductions were effected in the Magnox reactors. The highest average annual effective doses, about 3.0 mSv, were at the Chapelcross reactors (the earliest of the designs). More detailed information can be found in the reviews of radiation exposures in the United Kingdom [H3, H9]. In this Annex no distinction has been made in Table 7 between the various types of GCRs.

123. The worldwide number of GCRs averaged over five-year periods has not differed by more than 10% from 40. The average number in operation during 1990–1994 was 38. The average annual energy generated increased over the four five-year periods from 5.4 GWa to 8.4 GWa in the most recent period. Over 90% of this energy was generated in the United Kingdom. The number of monitored workers increased overall from 13,000 to 30,000, as shown in Figure IV. The average annual collective effective dose dropped from 36 through 34 and 24 to 16 man Sv over the four periods. Over the 20 years, the normalized collective dose per reactor decreased, from 0.9 to 0.4, while the corresponding values for energy generation, man Sv $(GW\ a)^{-1}$, also decreased, from 6.6 to 2.0.

124. The average annual effective dose to monitored workers worldwide, averaged over five-year periods, fell progressively from 2.8 mSv in the first period by a factor of about 2 between each period, so that the value for 1990–1994 was 0.5 mSv. The fraction of the monitored workforce receiving annual doses in excess of 15 mSv has been small, decreasing from 0.02 by a factor of more than 100. Between 1992 and 1994 there was only one instance of a worker at a United Kingdom GCR exceeding 15 mSv in a year, and only 10 workers exceeded 10 mSv in a year [H9].

4. Light-water-cooled graphite-moderated reactors

125. LWGRs were developed in the former USSR and have only been installed in what is now the Russian Federation and Lithuania. No data for LWGRs were reported in the UNSCEAR Survey of Occupational Radiation Exposures, but data relating to the two countries have been obtained from ISOE and other sources [L5, R2]. Data on energy generation were taken from Annex C, "*Exposures to the public from man-made sources of radiation*".

126. Overall the number of LWGRs increased, from 12 in the first period to 20 during 1990–1994, and the corresponding average annual energy generation increased, from 4.4 to 9.4 GWa. The number of monitored workers increased over the first three periods, from about 5,000 to 13,000, but no data are available for 1990–1994. The average annual collective effective dose increased significantly over the periods, from 36 to 62 to 170 to 190 man Sv. This increase is also reflected in the normalized collective dose values; that per reactor rose from 3.0 to 9.4 man Sv and that for energy generation rose from 8.2 to 20.3 man Sv (GW a)$^{-1}$. The average annual effective dose to monitored workers is estimated to have risen from 6.6 mSv in the first period to 13 mSv in the third. No data are available for 1990–1994, but given that the collective dose rose relative to the preceding period it is likely that the exposure of monitored workers also increased. No data have been available on the fractions NR_{15} or SR_{15}, but the other data suggest that they must be significant.

127. It was suggested in the UNSCEAR 1993 Report [U3] 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 exposure.

5. Summary

128. Data on occupational exposure at reactors worldwide are summarized in Table 8. The worldwide number of power reactors averaged over the five-year periods increased from about 190 in the first period to 421 in 1990–1994. The corresponding increase in average annual energy generation was from 55 to 230 GWa. Averaged over the whole period about 85% of the total energy was generated in LWRs (of this about 70% was from PWRs and 30% from BWRs), with contributions of about 5% each from HWRs, GCRs, and LWGRs. The number of monitored workers increased from about 150,000 to 530,000. The period 1990–1994 is the first for which a reasonably robust estimate of measurably exposed workers, some 290,000, is available.

129. The annual collective effective dose averaged over five-year periods increased over the first three periods (600, 1,000, and 1,100 man Sv) but has fallen back to 900 man Sv for 1990–1994. The trends in annual values are shown in Figure V. About 80% of the collective dose occurred at LWRs, with broadly similar contributions from PWRs and BWRs despite the fact that they were more than twice as many PWRs as BWRs. Averaged over all the periods, the contribution from HWRs has been 5%, that from GCRs 3%, and that from LWGRs about 13%.

130. The normalized collective effective dose per reactor averaged over all reactors rose between the first two periods, from 3.2 to 3.6 man Sv, but dropped to 2.8 and then 2.1 man Sv over the last two periods. The corresponding figures per unit energy generated are 11, 10, 5.9, and 3.9 man Sv (GW a)$^{-1}$. 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 four periods.

131. The annual effective dose to monitored workers averaged over all reactors fell steadily, from 4.1 mSv to 1.4 mSv. For the 1990–1994 period, data were available to enable an estimate of the annual effective dose to measurably exposed workers of 2.7 mSv. 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.

132. 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 8. 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 <0.01 in 1990–1994. The corresponding fraction of the collective dose arising from doses in excess of 15 mSv decreased from 0.60 to 0.08.

E. FUEL REPROCESSING

133. Commercial-scale reprocessing of irradiated spent fuel from nuclear power facilities to recover uranium and plutonium is performed in only two countries, France and the United Kingdom. Smaller facilities are in operation in Japan, India, and the Netherlands (experimental facility), and the Russian Federation has been reprocessing fuel for reactors developed in that country. Although the process varies depending on the nature of the fuel reprocessed, it generally involves the dissolution of the spent fuel elements in an acid bath, followed by the chemical separation of uranium and plutonium from the fission products and other actinides produced in the fuel. In spite of the fact that most fuel elements are cooled for up to several years before being reprocessed, they still contain high levels of radioactive materials at the time of reprocessing, and remote operations and heavy shielding are necessary for the adequate protection of workers.

134. Data on occupational exposure in reprocessing plants are summarized in Table 10. The UNSCEAR 1993 Report [U3] analysed the differences between plants reprocessing metal fuel and oxide fuel. The UNSCEAR Survey of Occupational Radiation Exposures for 1990–1994 made no such differentiation. The numbers of plants involved in reprocessing worldwide is limited, with the largest contributions during 1990–1994 coming from France, the Russian Federation, and the United Kingdom. While worldwide estimates have been derived, there are some significant differences between the data set for 1990–1994 and the sets for previous periods, and any comparisons

with previous worldwide estimates should be drawn with extreme caution. In the earlier periods the worldwide estimates of average annual collective effective dose were dominated by the contribution from the United Kingdom (65% over all three periods) and, to a lesser extent, by France (22%) and United States (13%). For 1990–1994, the Russian contribution of 33.9 man Sv accounted for over 50% of the worldwide average annual collective effective dose. As might be expected, this large contribution significantly increased the worldwide estimate, some 67 man Sv, in contrast to the three previous periods, during which the worldwide average annual dose declined, from 53 to 47 to 36 man Sv. If the Russian data had been excluded, the downward trend would have been maintained.

135. Given the confounding impact of the Russian data, it is perhaps more instructive to look at trends in the individual countries. The number of monitored workers in France, Japan, and the United Kingdom all increased by about 30% relative to the preceding period and by a factor of between 2 and 4 relative to 1975–1979. In the United Kingdom, the average annual collective effective doses over the four five-year periods steadily reduced: 47, 40, 29 and 21 man Sv. The corresponding figures for France were about 13 man Sv in each of the first three periods but only 4.7 man Sv for 1990–1994. The data for the smaller reprocessing operations in Japan rose over the first three periods, from 0.38 to 1.8 man Sv, and then decreased, to 0.82 man Sv. The data for the United States relate to Department of Energy facilities [D4], which are mainly associated with defence activities, but as was done for earlier UNSCEAR reports, they have been included under reprocessing. The apparent rise in the number of monitored workers in the United States is likely to be related to changes in monitoring practices rather than to any increase in the activity. (This matter is addressed more fully in Chapter VI, Defence Activities). Compared with the previous period, the average annual collective effective dose in 1990–1994 decreased by a factor of about 3, from 4.9 to 1.6 man Sv; a similar reduction from 2.7 mSv to 0.82 mSv is seen in the values for doses to measurably exposed workers.

136. The average annual effective dose to monitored workers fell consistently over the four periods for both France, from 2.9 to 0.36 mSv, and the United Kingdom, from 8.3 to 2.0 mSv. The Japanese data follow the pattern for collective dose, with a rise over the first three periods from 0.44 to 0.98 mSv and a drop to 0.32 mSv for 1990–1994.

F. WASTE MANAGEMENT

137. The volume of radioactive waste from the nuclear fuel cycle (and also from medical and industrial uses) is increasing, with very little having been moved thus far to final waste repositories. Consequently, doses associated with waste management are of increasing importance. However, in the dose data currently available, the data specifically associated with waste management are rarely identified separately. This is a matter that needs to be addressed in future reviews, which could include an indication of the general magnitude of the practice and the present exposures to workers involved.

138. While no data are readily available on exposures, there are some data on the magnitude of the practice in relation to the nuclear fuel cycle. A review by IAEA [I21] of the nuclear fuel cycle and waste management gives an overview for 1993 that can be considered typical for the period. At that time there were 301 research and test reactors in operation, 14 under construction, and 260 shut down. Of the total, 90 that were in operation, 6 that were under construction, and 9 that were shut down were in developing countries. Most of the reactors had been built 25–30 years earlier, when it was assumed that the irradiated fuel would eventually be shipped back to the country of origin. This has frequently not been possible. In some countries, highly enriched, high-burn-up fuel is stored in facilities that were not designed for such long-term storage. While the management of spent fuel from research reactors poses its own problems, the overall spent fuel problem is dominated by fuel from power reactors. There are a number of strategies for dealing with spent fuel: some is stored at the reactors, some at centralized facilities away from the reactor, and some is reprocessed, generating high-activity waste. Finding a permanent repository for active waste has so far proved to be an intractable problem in the vast majority of countries, and a number of interim storage facilities have been developed, based on either wet storage in ponds or dry storage facilities.

139. In 1993 the spent fuel arising from all types of reactors was about 10,000 t HM (heavy metal), giving an estimated cumulative total of over 145,000 t HM. About 95,000 t HM was being stored in 1993, which was over 20 times the annual reprocessing capacity at that time. The storage capacity at reactors was estimated to be about 59,000 t HM, 94% of it wet storage and 6% dry storage. To date, the doses associated with the management of spent fuel have been subsumed into data for reactor operation, reprocessing, and research, with different countries taking different approaches. The growing computerization of dose records and the advent of active personal dosimeters could make it possible to segregate dose data and allow doses associated with waste management to be separately identified.

140. Although the management of spent nuclear fuel is a major source of exposure from nuclear waste, there are others, notably the management of waste industrial and medical sources and the decommissioning of nuclear facilities. The latter will lead to a growing proportion of the waste managed, and data will be needed for doses arising in decommissioning to carry out a comprehensive assessment of the doses from waste management.

G. RESEARCH IN THE NUCLEAR FUEL CYCLE

141. It is difficult to estimate the levels of occupational exposure that can unequivocally be attributed to research and development in the commercial nuclear fuel cycle. Few data are reported separately in this category, and even when they are, uncertainties remain as to their proper interpretation. The main difficulties of interpretation are as follows:

(a) data are often compiled for research establishments whose main, but not sole, function is to undertake research and development associated with the commercial nuclear fuel cycle. The fraction devoted to this function is rarely given;
(b) some fraction of the occupational exposures attributed in the preceding Sections to particular parts of the fuel cycle contains a contribution from research and development, but the magnitude of this fraction is difficult to estimate;
(c) collective doses from research have been normalized in terms of the nuclear energy generated in the year in which the research was performed. While this convention has the benefit of simplicity, practicability, and convenience, the validity of utilizing current levels of collective dose and energy generation is open to criticism. The benefits of research inherently accrue over a period quite different from that in which the research was performed, and the normalization should in fact take account of the total energy generated in the period in which the benefits are deemed to accrue. In a rapidly developing industry, it is evident that normalization based on current energy generation is likely to lead to a large overestimate in the early years, followed by an underestimate later, as the industry matures and the amount of research declines.

142. Occupational exposures arising in nuclear research, averaged over five-year periods, are summarized in Table 11. 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 reported annual collective effective doses range from a very small fraction of a man sievert (e.g. in Finland) to about 38 man Sv in the United Kingdom for the earliest period. Country-to-country differences are to be expected in the occupational exposures associated with this category; however, these differences may have been exaggerated significantly by different reporting approaches. The collective effective dose attributed to research in the three previous periods has been dominated by the contributions from the United States and the United Kingdom. Each has shown a steady downward trend, from 33 to 19 man Sv and from 38 to 24 man Sv, respectively, over the first three periods. For 1990–1994, the contribution from the United Kingdom fell dramatically, to 5.6 man Sv. This and the halving of the number of monitored workers reflects both better protection standards and a large reduction in the United Kingdom's nuclear research programme. Comparable data are not available from the United States. The largest contribution in the 1990–1994 period came from the Russian Federation, which reported an average annual collective effective dose of about 16 man Sv (over the years 1992–1994). This is the first period for which data have been available. The only other countries reporting annual doses of 1 man Sv or greater are Canada, France, India, and Japan; each of which has a significant nuclear research and development programme. In each case, while the extent decrease varies, there has been a downward trend in collective dose.

143. Worldwide levels of occupational exposure associated with research are also given in Table 11. They were estimated from the reported data, with extrapolation based on GDP. This method was adopted in preference to the extrapolation used for other parts of the nuclear fuel cycle, which were based on fuel fabricated, energy generated, etc.; the difficulties, identified previously, of using energy generation as a basis for normalizing research were responsible for the change to GDP. The GDPs of the countries reporting data represented about 40% of the worldwide total. On average, therefore, the reported data have been scaled upwards by a factor of about 2.5; there is, however, considerable variation about this average for particular regions.

144. The annual number of monitored workers in research worldwide, averaged over five-year periods, has remained remarkably constant at between 120,000 and 130,000. The average annual worldwide collective effective dose dropped from 170 to 100 man Sv over the first three periods and was slightly lower, 90 man Sv, for 1990–1994. This profile is mirrored in the worldwide estimates for the annual effective dose to monitored workers, which fell from 1.4 to 0.82 mSv over the first three periods and decreased marginally to 0.78 mSv for 1990–1994. There is a similar profile for the fraction of the monitored workforce exceeding 15 mSv, which dropped from about 0.04 to <0.01. The corresponding figures for the fraction of the collective effective dose arising from annual doses in excess of 15 mSv has shown a more steady reduction, with values of 0.42, 0.39, 0.30, and 0.22. It should be noted that there are some considerable variations between countries and that for 1990–1994 no dose distribution data were available for the largest contributor to the collective dose, the Russian Federation. For the first time, reasonable data were available on doses to measurably exposed workers, and the average value worldwide was estimated to be 2.5 mSv; greater by a factor of 3 than the average annual dose to monitored workers.

145. Some of the problems of making meaningful estimates of the normalized collective dose (relative to energy generated) were identified in paragraph 141. They involve how to deal with the different temporal distributions of the benefits and costs of research. This was discussed in some detail in the UNSCEAR 1993 Report [U3], where it was concluded that for the purpose of assessing overall values of normalized collective doses for the whole fuel cycle, a value of 1 man Sv $(GW\ a)^{-1}$ could be assumed to be generally applicable for research, irrespective of when it was undertaken. The con-tinued applicability of this approach has been reviewed and confirmed.

H. SUMMARY

146. Trends in worldwide occupational exposures from each stage of the commercial nuclear fuel cycle are summarized in Table 12 and illustrated in Figures VI and VII. The data are annual averages over five-year periods. During the first three periods, the number of monitored workers in the commercial fuel cycle rose, from about 560,000 to 880,000, but in 1990–1994 the number fell to 800,000 (Figure VI). This was largely due to a three- to fourfold reduction in the estimated number in the mining sector, from 260,000 to 69,000. The latter figure may be an underestimate attributable to the limitations of the data set, but all the other indicators support a significant reduction in this component of the monitored workforce. In the first five-year period mining accounted for over 40% of the workforce, but over the four periods reactor operation has become the dominant component of the monitored workers and at 530,000 now accounts for about 65% of the total.

147. The average collective effective dose, averaged over five-year periods, initially increased from 2,300 to 3,000 man Sv but in the last two periods decreased to 2,500 and then 1,400 man Sv (Figure VII). This almost twofold decrease between the last two periods is again dominated by a reduction by a factor of 3 to 4 in the collective dose from mining. The same cautions noted in the preceding paragraph apply here, but the supporting evidence of a general reduction in collective dose over all the countries and the cessation of underground mining in a number of countries make it more likely that the values are not significant underestimates.

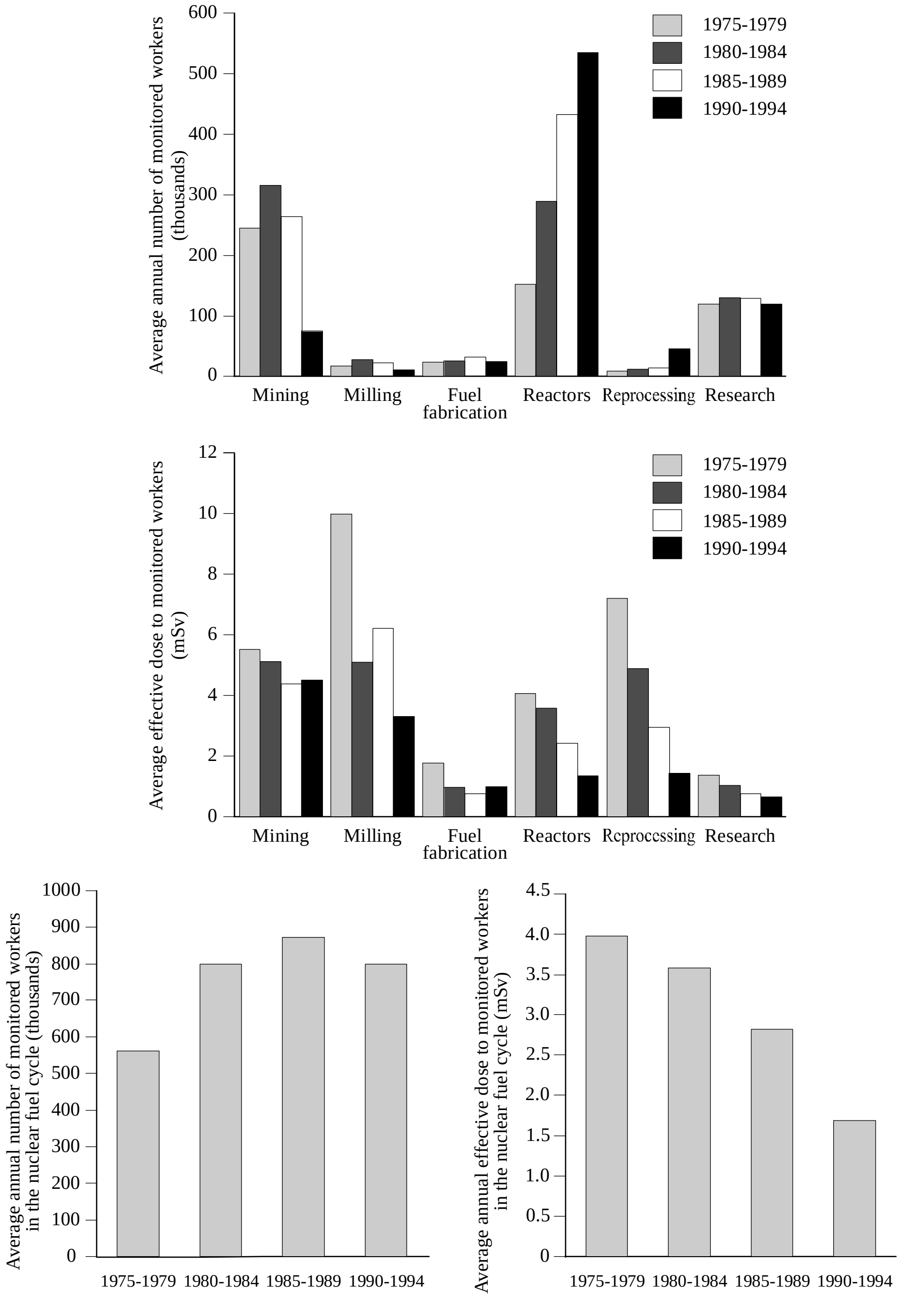

Figure VI. Trends in numbers of monitored workers and doses to workers in the nuclear fuel cycle.

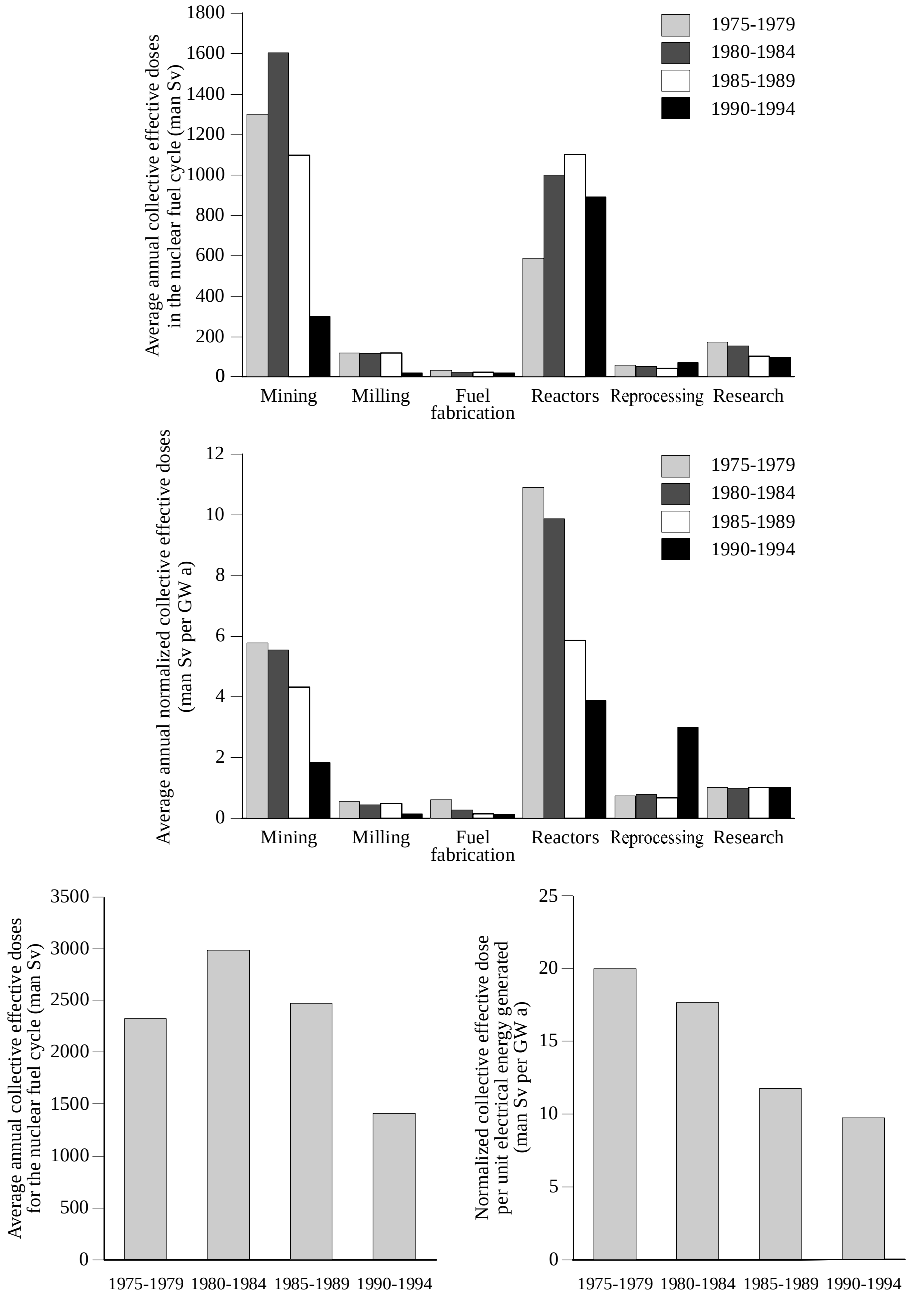

Figure VII. Trends in collective doses and normalized collective doses in the nuclear fuel cycle.

148. The average annual effective dose to monitored workers in the fuel cycle has decreased progressively, from 4.1 mSv in 1975–1989 through 3.7 and 2.9 mSv to 1.8 mSv in 1990–1994. There is considerable variation about these averages for the different stages of the fuel cycle. However, apart from the mining stage of the nuclear fuel cycle; where doses have been generally static at about 5.0 mSv, the overall downward trend is evident in all the other stages of the nuclear fuel cycle. For 1990–1994, there is for the first time a reasonably robust estimate of the average annual effective dose to measurably exposed workers. The estimated value of 3.1 mSv represents an increase in the value for monitored workers by a factor of just under 2. This factor varies considerably between the stages of the nuclear fuel cycle. The fraction averaged over five-year periods of monitored workers receiving annual doses in excess of 15 mSv (NR_{15}) has decreased from about 0.20 to about 0.01; the corresponding decrease in the fraction of the collective effective dose (SR_{15}) has been from about 0.63 to about 0.11. In the light of these reductions it has become relevant to look at the dose profiles in more detail. Accordingly, in the 1990–1994 UNSCEAR Survey of Occupational Radiation Exposures, additional data were sought for the ratios relevant to 10, 5, and 1 mSv. This effort is far from complete, but it provides a reasonable dose profile within the various stages of the nuclear fuel cycle that will serve as a baseline for future reviews.

149. The normalized collective effective doses for each stage of the fuel cycle are shown in Figure VII. The collective dose from mining, milling, fuel fabrication, and fuel reprocessing have been normalized to the energy equivalent of uranium mined or milled or to the fuel fabricated or reprocessed in the respective periods. For research associated with the fuel cycle, 1 man Sv $(GW\ a)^{-1}$

has been assumed in each period. The overall normalized collective effective dose (i.e. averaging over all stages in all fuel cycles and taking account of their relative magnitudes) is estimated to be (in chronological order) 20, 18, 12, and 9.8 man Sv (GW a)$^{-1}$ for the four periods. This again shows an overall downward trend.

III. MEDICAL USES OF RADIATION

150. Radiation is used in medicine for both diagnostic and therapeutic purposes. The physicians, technicians, nurses, and others involved constitute the largest group of workers occupationally exposed to man-made sources of radiation. The wide range of applications and the types of procedures or techniques employed in the context of patient exposure are reviewed in Annex D, "*Medical radiation exposures*", where changes in practice and possible future trends are also discussed. Consideration is limited here to the occupational exposures that arise from the application of these procedures. Data on occupational exposures are presented for workers in each of the following areas: diagnostic radiology, dental radiology, nuclear medicine (diagnostic and therapeutic), radiotherapy, other medical practices, and all medical uses of radiation grouped together.

151. Previous Chapters of this Annex contained cautionary remarks about the accuracy or validity of reported statistics on occupational exposures and the extent to which they can be fairly compared, either between countries for the same occupational group or between occupational groups in the same or different countries. It is in the area of medical uses of radiation where these cautionary remarks are most important, and great care must be exercised in interpreting and evaluating the various statistics. In the medical field, an important difference is where the dosimeters are located (in particular, whether they are above or below lead aprons when these are worn). Two more factors complicate matters: firstly, the radiation that contributes most to the overall occupational exposures from the medical uses of radiation is non-uniform and of low energy and, secondly, the approach used to derive effective doses from dosimeter measurements can have important implications for the comparability of occupational exposures.

152. Some of the above differences can been seen in Table 2 and in the notes to the various tables covering medical uses. However the information is patchy, and it has proven impracticable in this analysis to revise or normalize the reported exposures to ensure that they can be fairly compared. Accordingly, when worldwide levels of exposure were estimated from the available data, no distinction was made between doses measured, recorded, or reported in different ways; all reported doses were assumed to be adequate surrogates for effective dose. More attention needs to be given to this matter to afford better comparability between doses arising in different circumstances and to enable more reliable estimates of worldwide levels of occupational exposure.

153. National data for the various categories of medical uses of radiation averaged, where possible, over five-year periods, are given in Table 13. It should be noted that some countries do not keep data divided into the various medical use areas, so their reported data appear in the "all other medical uses" part of Table 13. To provide a more secure basis for estimating worldwide exposures, all the data provided on medical uses have been aggregated by country (Table 14). The reported data have also been aggregated by region (Table 15).

154. Worldwide levels of exposure have been estimated from the national data by extrapolation within particular regions based on GDP, as described in Section I.E. In general the collective dose for each practice correlated well with GDP, but there were exceptions for some countries. The degree of extrapolation needed varied with medical use and, more importantly, by region. The vast majority of extrapolations were by a factor of from 1.5 to 5. However, for eastern Europe and the remainder regions, the factor was typically 20, in the first case mainly because there were no data from the former USSR, and in the second because so few countries provided data. Nevertheless the regional estimates are consistent with those for previous periods.

155. Summaries of the worldwide exposures, by practice and by region, are given in Tables 16 and 17, respectively. Formally, the United States was treated as a separate region and the rest of the OECD as another region. In this Annex the main confounding factor in deriving the worldwide exposure estimates has been the absence of data for the United States. As was noted in Section I.E, the Committee has developed an approach for estimating collective dose where no regional data are available. In essence this estimates the regional dose by prorating the sum of the GDPs for the total collective dose reported. This approach generally worked well, but it produces figures for the United States that are significantly lower than for previous reporting periods and therefore calls into question the appropriateness of the normal method of estimation.

156. The Committee has considered alternative methods of estimating the values for the United States. The region most similar to the United States in this respect is the rest of the OECD. Earlier UNSCEAR reports derived for each region the collective effective dose per unit GDP (man Sv per 10^{12} United States dollars). While there have been clear differences in these values for the two regions, the values have been converging. For the last three five-year periods, the ratios of this parameter for the United States to that for the rest of the OECD have been 3.4, 2.8, and 2.4 in chronological order. It would therefore be reasonable to presume that the convergence has continued and that a ratio of approximately 2.0 would be appropriate for

1990–1994. The ratio of the GDPs for the two regions is approximately the inverse of this, namely 0.5. On this basis the values for the United States approximate to those for the rest of the OECD. World estimates using this approach are included in Tables 13, 14, 16, and 17. The resulting values for the United States are consistent with the trends of increase in number of monitored workers and decrease in annual collective effective dose observed over the first three periods. Similar consistent trends are found in the world estimates calculated by this method. For comparison, world estimates based on the method described in Section I.E are given in brackets in the tables.

A. DIAGNOSTIC RADIOLOGY

157. It is noted in Annex D, "*Medical radiation exposures*" that during the last 20 years, medical imaging has undergone a technological revolution; steady advances in the quality of x-ray images and in patient protection have ensured a continuing role for diagnostic x-ray use in health care, although alternative modalities for diagnosis, such as ultrasound and, particularly in developed countries, magnetic resonance imaging (MRI), are becoming increasingly available. Nevertheless, x-ray examinations remain the most frequent use of ionizing radiation in medicine. Occupational exposure in medicine depends on a number of factors, the most important of which is the x-ray procedure. There are three general procedures that constitute sources of exposure: radiography, fluoroscopy, and special examinations. Radiography here is taken to include general-purpose radiography, computed tomography, and mammography. Special examinations are taken to include cardiac catheterization, angiography, and interventional procedures.

158. Workload is an important factor; in general, occupational exposures are directly proportional to the workload [N3]. Training and the use of protective aprons are relevant, particularly in the control of exposures during fluoroscopy and special examinations.

159. Radiography is by far the most widely used x-ray imaging technique. During radiography with fixed installations, the radiographer would normally be expected to stand in a control booth that is typically shielded as a secondary barrier against x-ray tube leakage and scattered radiation from the room and 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 [N3]. Mobile units, however, operate in an unshielded environment and are therefore of greater concern.

160. Although doses to patients from computed tomography (CT) may be high, the exposure of staff 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, computed tomography does not represent a significant source of exposure. Only if an individual is required to remain in the room with the patient during examination can a measurable exposure be expected.

161. Fluoroscopic procedures, including those of a special nature, constitute fewer than 10% of all examinations in the United States [N2] but are by far the largest source of occupational exposure in medicine. During fluoroscopy, the x-ray tube may be energized for considerable periods of time. Fluoroscopic procedures require the operator to be present in the examination room, usually close to the patient. In fact, the patient is the main source of exposure because of scattered radiation.

162. In special examinations, fluoroscopic times may be long and the accompanying radiographic exposures can be numerous. Staff are nearly always present in the room close to the patient, and it is difficult to shield against scattered radiation. Staff exposure rates associated with the examinations in such rooms can be 2 mGy h^{-1} or more, depending on location and fluoroscopic technique. Cardiac catheterization, in particular, can constitute a source of relatively high exposure. Procedures involve not only radiography and fluoroscopy, some also require cineradiography. During cineradiography, the table-top air kerma rate may vary from 0.2 to 1 Gy min^{-1}. Although an examination may require only 30–40 seconds of cinegraphic time, total exposures to staff can be high [N3].

163. Data on occupational doses from diagnostic radiology from the UNSCEAR Survey of Occupational Radiation Exposures are given in the first part of Table 13 and Figure VIII. The reported number of monitored workers for the 1990–1994 data set is about two thirds of the number for the previous five-year period, but from a wider range of countries. The countries reporting data on occupational exposures from diagnostic radiology accounted for about 20% of the GDP worldwide. This compares with 18% for the countries reporting data for the preceding five-year period [U3].

164. The last three periods have shown an increasing trend in the annual number of monitored workers involved worldwide in diagnostic radiology. However, the estimate for the present period, 950,000 (compared with 1.4 million for 1985–1989), appears to indicate a reversal of this trend. Similarly, the estimated annual average collective dose is significantly reduced: 470 man Sv compared with 760 man Sv for the preceding period. These comparisons should be regarded with caution, because unlike in earlier years, the questionnaire completed by countries included a category "all other medical uses". Some countries were only able to provide data covering all medical uses aggregated together, and they reported them under "all other medical uses". If the worldwide estimates deriving from the "all other medical uses" category were to be distributed among the named medical practices in proportion to the world estimates for these practices, then the worldwide estimates for diagnostic radiology for 1990–1994 would increase to 1.3 million monitored

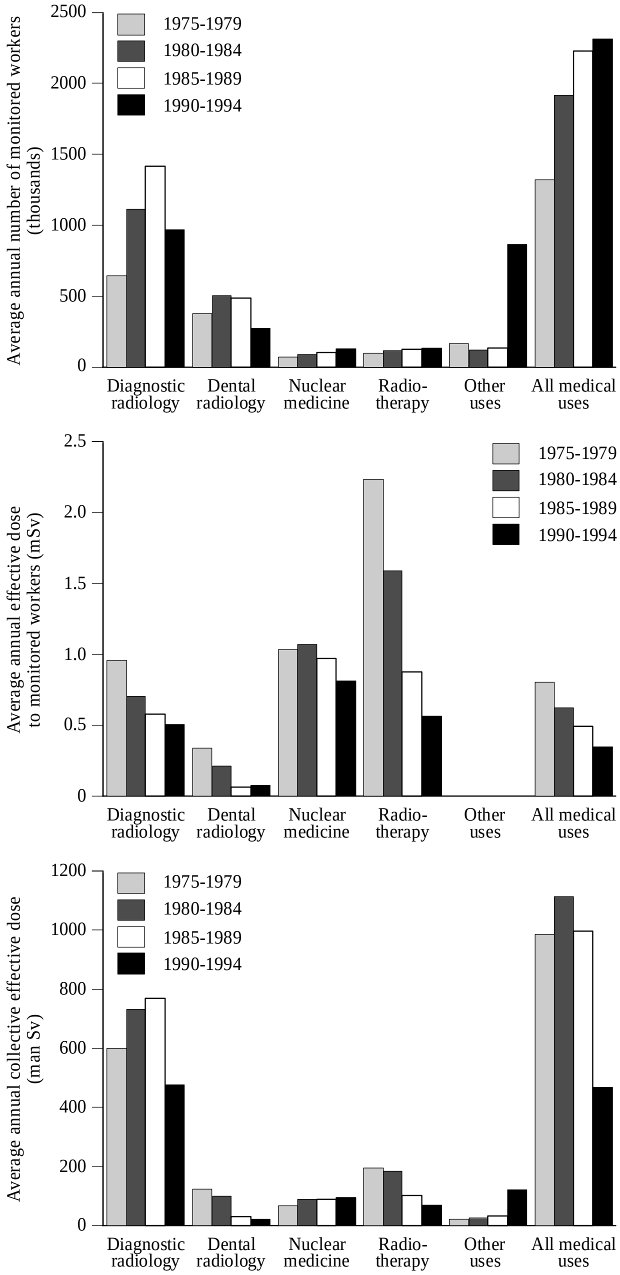

Figure VII. Trends in number of monitored workers, doses to workers and collective doses for medical uses of radiation.

workers with an annual collective effective dose of 540 man Sv. These figures are more in line with those from 1985–1989 but still show a downward trend. This could be explained by a possible move in OECD countries (which dominate the data) to cut back on the monitoring of staff in response to economic pressures and also by the impact of efforts to improve radiological protection practices.

165. The average annual effective dose to monitored workers averaged over the four five-year periods has fallen from 0.94, through 0.68 and 0.56 to 0.50 mSv for 1990–1994. This same downward trend is evident in the data for most countries and regional groupings, but there is considerable variation between countries in the level of dose and the extent of the decrease. Most average annual doses are below 1.0 mSv, but somewhat higher values are reported for Pakistan, Peru, the Syrian Arab Republic, and the United Republic of Tanzania. The data set for 1990–1994 contained more data on the numbers of measurably exposed workers and the doses they received. This has enabled a more robust worldwide estimate of this parameter: 1.3 mSv; it is higher by a factor of 2.7 than that for monitored workers.

166. Some data from the United Kingdom, given in Table 18, show the breakdown of exposures by occupational grouping for some diagnostic radiology departments [H3]. It can be misleading to compare the calculated averages for groups because of the large number of low doses, but some conclusions can be drawn on the basis of these data. Radiographers receive less than 0.1 mSv in a year, whereas radiologists receive a few times more. Cardiologists tend to be the most exposed; their average annual dose was 0.4 mSv, and an appreciable proportion received more than 1 mSv.

167. Tables 19 and 20 show the distribution of doses for the medical sector in Spain [H8] and France, respectively [C3]. The Spanish data also show the distribution for 1989 and include other use sectors. In 1989 in Spain the number of medical sector workers exceeding 20 mSv (90) was greater than the number in the nuclear fuel cycle sector. By 1995 there had been a significant drop in this number (to 22) and in the collective dose and the average individual dose. The higher doses are in diagnostic radiography and particularly in interventional radiology. This picture is also reflected in Table 20, which gives the French data for 1995. According to these data, 31 persons in diagnostic radiology exceeded the value of 50 mSv in that year. Worldwide there have been a number of instances of deterministic skin effects arising from long fluoroscopic exposures [F2, W5].

168. Regional variations in the data for each medical sector are given in Table 15. For diagnostic radiography, the regional average individual annual dose is generally 0.3–0.4 mSv; however, average doses greater than 1 mSv are derived for east Asia, Latin America, and the remainder region.

B. DENTAL PRACTICE

169. In almost every dental office or clinic, a diagnostic x-ray machine is available and frequently used. The number of x-ray devices used in dentistry is thus extremely large. For example, in France in 1993 more than 35,000 devices were estimated to be installed [V1]. Occupational exposure in dentistry is from 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 but a steady decrease in the collective dose [N3]. A majority of dental practitioners do not receive measurable doses, and indeed some regulatory authorities do not require routine individual monitoring except where the workload is high.

170. The sum of the GDPs for those countries reporting data was about 50% of the worldwide total in the first five-year period, increasing to 60% in the third. For 1990–1994, this share decreased to 40%, largely due to the absence of data from the United States. On average, therefore, the data have been scaled up by a factor of 2.5 but with considerable variation about this average value for particular regions. However, it has to be noted that the United States data in previous periods dominated world estimates out of proportion to the country's GDP. For example, in 1985–1989 the United States data accounted for 64% of the worldwide estimates of monitored workforce and 74% of the annual collective effective dose. Therefore, while worldwide estimates have been made for 1990–1994, it may be instructive to also compare the worldwide estimates with the United States data subtracted.

171. The estimates of the worldwide average annual number of monitored workers (Table 13) for the preceding three five-year periods were 370,000, 500,000, and 480,000, so that the estimate of 265,000 for 1990–1994 appears to depart from these figures. If the data for the United States are removed, then the figures, in chronological order, are 155,000, 241,000, 173,000, and 147,000. This suggests broad comparability over the four periods and, perhaps, the sensitivity of the estimation methods to the profile of the data sets.

172. The average annual collective dose was about 120 man Sv in the first period, decreasing to about 25 man Sv in the third, with most of the decrease having occurred between the second and third periods. The corresponding estimate for 1990–1994 is 16 man Sv, continuing the downward trend. The earlier periods were dominated by United States data, but if these are subtracted, the values for the four periods are 40, 30, 13, and 10 man Sv, still a downward trend. It would be reasonable to expect the United States to continue to show a downward trend. Therefore the worldwide estimate for annual collective effective dose of 16 man Sv is considered more robust than the estimate of the number of monitored workers. It can be stated with some confidence that dental radiology does not contribute significantly to medical occupational exposures.

173. The annual effective dose to monitored workers worldwide averaged over five-year periods fell progressively, from 0.32 mSv in the first period to 0.05 mSv in the third. The estimate for the fourth period, 0.06 mSv, is a marginal increase but well within statistical uncertainty and in any case a low value. The regional values are within a factor of 5 of the overall average but still low. However there is considerable variation for some countries.

174. During 1990–1994 more data were reported for measurably exposed workers and dose distributions. The value of 0.28 for SR_{15} is approximately twice that for the preceding period. High individual doses in dentistry are not unknown; however, it is probable that the recorded doses reflect not the actual exposure of individuals but the fact that personal dosimeters are once in a while left in areas where they could be irradiated. Given the relatively low collective dose and average individual doses, it would not take many such instances to distort the collective dose distribution.

C. NUCLEAR MEDICINE

175. Whereas the broad aim in diagnostic radiology is the imaging of anatomy, that in nuclear medicine is more 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 the exposures when performing clinical nuclear medicine procedures depends on the precautions taken, including the use of syringe shields when performing the injections. Personnel must be close to the patient when giving the injections and while positioning the patient and camera. Usually, the imaging process makes the greatest contribution to the exposure of staff [B1]. Internal exposures of personnel are usually much less than external exposures; they are controlled by monitoring work surfaces and airborne concentrations, although some medical centres conduct routine bioassays [N3].

176. The total number of nuclear medicine procedures performed in the United States at the start of the 1990s was about 100 million; some 90% of these were radioimmunoassay investigations, and the remainder were *in vivo* administrations of radioactive materials. The number of *in vivo* nuclear medicine procedures increased by about 16%, from 6.4 million to 7.4 million per year from 1980 to 1990. This was less than the projected 8% per year increase expected over that period, because some techniques, such as the use of ^{99m}Tc for brain scintigraphy and ^{99m}Tc sulphur colloid liver imaging virtually disappeared. (Computed tomography and magnetic resonance imaging have largely replaced those techniques.) Some other techniques, such as positron emission tomography for mapping certain functions of the brain, show increasing use [N3]. The number of installations in France approved to undertake nuclear medicine in 1993 was 257 for *in vivo* therapeutic or diagnostic uses of radionuclides and 202 for *in vitro* uses [V1].

177. Radionuclides used for organ imaging, for example ^{99m}Tc, emit penetrating gamma radiation and give rise to the 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^{-1} 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^{-1} at 1 m from the patient, who will normally need to be segregated to reduce the exposure of other persons in the vicinity. Samples of blood taken from a patient also represent a source of staff exposure. Work involving the preparation and assay of radiopharmaceuticals tends to be associated with the highest occupational exposures in this field and

can give rise to annual doses up to about 5 mSv. Doses to hands and fingers can range up to the annual limit of 500 mSv, and 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 [N5].

178. Since the data on occupational exposure arising in nuclear medicine rarely distinguish between diagnostic and therapeutic applications, the present analysis is directed to overall levels of exposure in the field. Consideration is limited here to effective dose, to which extremity doses do not contribute. However in view of the potential for significant extremity doses in nuclear medicine, these would merit attention in any future analysis.

179. The sum of the GDPs for those countries reporting data accounted for about 12% of the worldwide total in the first period, rising to 18% for the third. The proportion for the present analysis was 19%, and allowing for regional reporting differences, on average the reported data have been scaled up by a factor of 7 but with considerable variation about this average value for particular regions and periods.

180. The annual number of monitored workers, averaged over the five-year periods, in nuclear medicine worldwide have steadily increased, with 61,000, 81,000, 90,000, and 115,000 being the estimated values for the four periods (see Tables 13 and 16). The corresponding values for the average annual worldwide collective effective dose are 62, 85, 85, and 90 man Sv. The annual effective dose to monitored workers worldwide, averaged over five-year period, varied little over the first three periods, with a typical value of 1.0 mSv. However, the estimated value for 1990–1994 was lower, 0.79 mSv. There were some regional variations, most notably for the Indian subcontinent and Latin America, which had values of about 2.3 mSv. Similarly, there are national variations, in particular for Pakistan and Peru, where somewhat higher doses were experienced. The worldwide average annual dose for measurably exposed workers during 1990–1994 was 1.4 mSv, with the values for the Indian subcontinent and Latin American being about 4.0 mSv.

181. The fraction of the monitored workforce worldwide receiving annual doses in excess of 15 mSv continues to be small. Indeed, only some 2% exceeded 5 mSv. This is the situation in most countries, but there are exceptions; in particular Pakistan (26% in excess of 15 mSv) and Cuba (13% in excess of 10 mSv). These variations are also evident in the distribution ratios for collective dose.

D. RADIOTHERAPY

182. Therapeutic uses of ionizing radiation are quite different in purpose from diagnostic radiological procedures. Radiotherapy is an important treatment modality for malignant disease (see Annex D, "*Medical radiation exposures*"). There are three main categories of activity in radiation oncology: brachytherapy, external beam treatment, and therapy simulation [N3]. Brachytherapy, where there is manual loading of the radioactive sources, is usually the most significant source of personnel exposure. Exposures may occur during receipt and preparation of the sources, during loading and unloading, and during treatment. Personnel should not normally be present in the treatment room when external beam therapy is being used, 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, occur from ^{60}Co teletherapy units as a result of leakage while the source is in the off position and from radiation that penetrates the barrier during use. The types of exposure from linear accelerators, betatrons, and microtrons depend on the type of beam (photon or electron) and the beam energy. Below 10 MeV, exposure comes 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 normally low. Exposures from simulators and other diagnostic imaging equipment used to plan treatments are also normally low [N3].

183. The data on occupational doses in radiotherapy from the UNSCEAR Survey of Occupational Radiation Exposures are included in Table 13. Data from the United Kingdom for specific groups of workers in a sample study are given in Table 21 [H3]. Relatively few beam radiographers, radiotherapists, technicians, or other support staff receive annual doses exceeding 1 mSv. With brachytherapy procedures, some theatre and ward nurses receive over 5 mSv in a year.

184. Worldwide levels of dose and numbers of workers involved in radiotherapy have been estimated from national data using the same extrapolation procedures as previously described. The coverage and scaling of the data were similar to that for nuclear medicine.

185. The annual number of monitored workers, averaged over five-year periods, in radiotherapy worldwide are estimated to have been 84,000, 110,000, 110,000, and 120,000 for the four periods chronologically. (Some 60% of these are employed in countries of the OECD.) The corresponding figures for the average annual worldwide collective effective dose are 190, 180, 100, and 65 man Sv. The last two five-year periods have seen fairly significant reductions in this parameter. While some of this decrease will have been due to general improvements in radiological protection arrangements, a large part of it probably came in brachytherapy, following the replacement of many radium sources by caesium sources and the widespread use of remote afterloading equipment.

186. The annual effective dose to monitored workers worldwide, averaged over five-year periods, fell consistently

over the four periods, with values of 2.2, 1.6, 0.87 and 0.55 mSv (chronological order). This downward trend is reflected in most of the countries reporting, although there are a few exceptions to the general level of average annual effective dose, most notably Pakistan and the United Republic of Tanzania, both of which reported values of about 10 mSv. The average annual dose to measurably exposed workers worldwide was 1.3 mSv, higher by a factor of about 2.7 than that to monitored workers. The fraction of monitored workers, averaged over the reported data, receiving annual effective doses in excess of 15 mSv was small, and indeed only 2% exceeded 5 mSv. This is similar to the figure for nuclear medicine as is the dose distribution for collective effective dose. The values for SR_{15} decreased from about 0.30 for the first period to 0.15 for the latest period. The noted higher average annual individual doses for Pakistan and the United Republic of Tanzania are also reflected in the distribution ratios NR and SR.

E. ALL OTHER MEDICAL USES OF RADIATION

187. The category “all other medical uses of radiation” was intended to cover the 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 being biomedical research. However, previous UNSCEAR reports contained a combined category, “all medical uses of radiation”, and this may have led to some confusion in completion of the questionnaire. It was possible to identify and eliminate from this category data that were simply an aggregation of data provided for the various practices. However the potential for a small degree of double counting cannot be eliminated. More importantly, some countries were not able to provide medical sector data in the various categories and opted to put all their data into this category. Indeed it is noticeable in Table 13 that there are some very large monitored populations (in excess of 100,000) in this category, which is unexpected. These data require clarification before they are interpreted; unfortunately, they account for about 68% of the data. In terms of numbers of monitored workers, this category accounts for some 65% of the total reported for all medical exposures. This could have been a significant confounding factor for the estimates made for the various categories of medical use. However, the problem mainly affects the OECD region (Germany and Japan), and the level of reporting over the other countries of the region was sufficient to ensure usable extrapolations in each of the categories. In view of the problem, no attempt has been made to produce world estimates for the “all other medical uses” category.

F. SUMMARY

188. National data on occupational exposures from all medical of radiation averaged over five-year periods are given in Table 14. Worldwide levels of exposure have been estimated from the reported data by extrapolation based on GDP. However it should be noted that in accounting for the lack of data from the United States, the method of estimation for the United States region was modified: the United States values were assumed to be equal to those of the rest of the OECD. This is discussed more fully in paragraph 156. In Figure IX, the collective effective doses from all medical uses of radiation in each country reporting data in 1990–1994 are shown in relation to GDP. The broad correlation between the two quantities is evident, with the degree of correlation generally increasing when consideration is limited to particular regions. For some countries in a geographical or economic region, the normalized collective dose (normalized in terms of the GDP) differed greatly from the average for that region. In most of these cases the values were much smaller than the average, suggesting that the reported data may have been incomplete, that much less use was being made of radiation in medicine, or that much higher standards of protection had been adopted in those countries. Similar observations have been made for the separate practices involving industrial uses of radiation. Notwithstanding these reservations on the completeness of some of the reported data, no attempt has been made to correct for this, and the reported data were all included in the estimation of worldwide levels of exposure. Any errors due to incompleteness of the reported data are unlikely to be significant in comparison with the uncertainty introduced by the extrapolation process itself and by the assumption that all of the reported doses are good surrogates for effective dose.

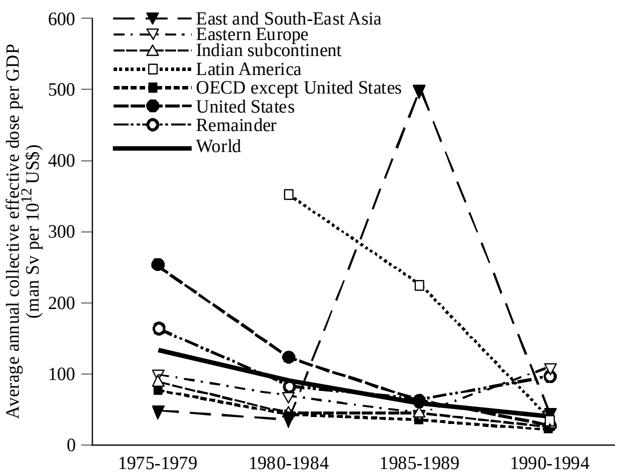

Figure IX. Trends in normalized collective effective dose (to GDP) for all medical uses of radiation.

189. The data on occupational exposures from all medical uses of radiation are presented for various geographic regions and economic groupings in Table 17. Because of its much larger normalized collective dose, the United States has been listed separately from the other OECD countries. Since the normalized collective doses for the respective periods were derived on different price bases (1977, 1983, 1989, and 1994, respectively), direct comparisons cannot be made without appropriate corrections. Within a given period, the normalized collective doses vary by a factor of about 2 between most

regions. The main exception to this in the first three periods was the United States, although some significant variations between periods for different regions are noted. The period 1990–1994 has seen a convergence of the normalized collective doses for the regions; a notable exception is eastern Europe. This may reflect the change in profile of reporting countries in the wake of the political changes taking place.

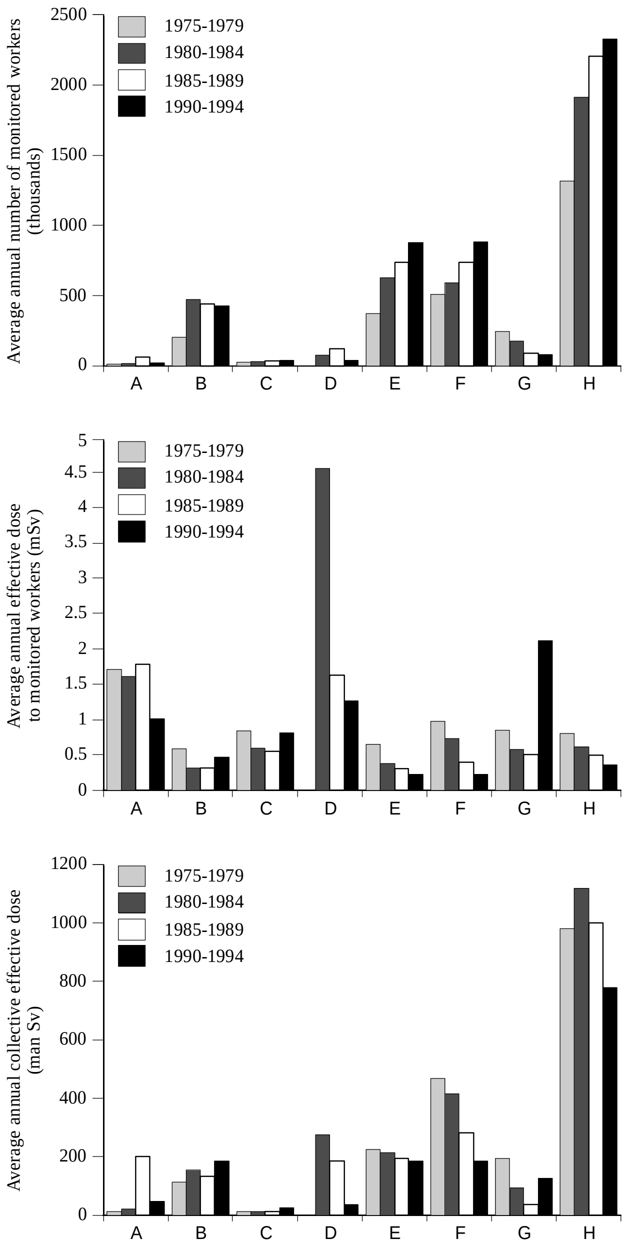

Figure X. Trends in numbers of monitored workers, doses to monitored workers, and collective doses for all medical uses of radiation.

A: East and South-East Asia
B: Eastern Europa
C: Indian subcontinent
D: Latin America
E: OECD except United States
F: United States
G: Remainder
H: World

190. The exposure data for the major regional groupings of countries are illustrated in Figure X. The worldwide annual number of monitored workers averaged over five-year periods is estimated to have increased from about 1.3 million through 1.9 and 2.2 to 2.3 million for 1990–1994. The majority of these workers were employed in the United States or in the rest of the OECD countries. Data for the four periods grouped by medical use sector are given in Table 16. As discussed in paragraph 187, the wording “all other medical exposures” is a confounding factor in the estimation of annual number of monitored workers, averaged over the 1990–1994 period, for the different medical uses. Caution should therefore be exercised in comparing these figures with previous periods. However the ratios between the use sectors are similar to those in the earlier periods and indicate that about 65% of the monitored workers are involved in diagnostic radiology, 20% in dental radiology, and 7% each in nuclear medicine and radiotherapy.

191. The worldwide annual collective effective dose, averaged over five-year periods, remained relatively uniform over the first three periods, about 1,000 man Sv. However, the UNSCEAR 1993 Report [U3] suggested that this might be an overestimate of the worldwide collective dose, with the diagnostic radiography contribution, which was the largest component, suspected of having been overestimated. The worldwide annual collective effective dose, averaged over 1990–1994, is estimated to have been 760 man Sv. This is a significant decrease relative to the previous periods and is consistent with the cautionary comments in the UNSCEAR 1993 Report [U3]. While a number of confounding factors have been identified in the extrapolations, the overall picture across the reporting countries is one of reduced collective doses; this finding provides a degree of confidence in the downward trend.

192. Over the four periods there appear to have been significant changes in the contribution of the different medical uses to the total collective dose. The contribution from diagnostic radiography rose, from 62% to 73% (A higher percentage, 78%, was recorded for 1985–1989, but as noted earlier, the validity of the data is somewhat suspect). The contributions from dental radiology and radiotherapy both decreased significantly, from 12% to 3% and 20% to 10%, respectively. Conversely, the contribution from nuclear medicine increased, from 6% to 14%.

193. The average annual effective doses to monitored workers involved in medical uses of radiation and the doses to monitored workers in each of the categories of medical use have, with two minor exceptions, consistently decreased over the four periods. The exceptions are the rise, from 1.01 mSv to 1.04 mSv, for nuclear medicine between the first and second periods and the insignificant rise for dental radiography, from 0.05 mSv in the third period to 0.06 mSv in the fourth period. The overall reductions over the four periods have been for diagnostic radiography, from 0.94 mSv to 0.50 mSv; for dental radiography, from 0.32 to 0.06 mSv; for nuclear medicine, from 1.0 to 0.79 mSv; and for

radiotherapy, from 2.2 to 0.55 mSv. Over the four periods the value for all medical uses decreased by a factor of about 2.4, to 0.33 mSv. Fewer data have been available for the average annual effective doses to measurably exposed workers, but relative to the preceding period the estimated value for 1990–1994 fell, from 1.7 to 1.4 mSv.

194. For 1990–1994 the fraction of monitored workers worldwide exposed to annual effective doses in excess of 15 mSv was small (less than 1% for each medical practice and for medical uses overall). Indeed for all medical practices, only 1% exceeded 5 mSv. For some individual practices this percentage rose to 2%. The value of SR_{15} decreased from about 0.14 to 0.10 between the first and second periods and then increased to 0.24 for the third. This was attributed to somewhat higher values for China, reported only for the third period. The value for 1990–1994, 0.14, reasserts the downward trend.

IV. INDUSTRIAL USES OF RADIATION

195. 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. As an example, in France, in 1993, there were 785 known x-ray generators and 850 gamma-radiography devices being used for non-destructive testing [V1]. In addition, there were 16 industrial accelerators, 85 irradiators, more than 10,000 gauges, and 200 x-ray fluorescence analysers. 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 small, which contributes to the lack of detail in recorded data. In the UNSCEAR 1993 Report [U3], 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 are used in the survey of data for 1990–1994: industrial irradiation, industrial radiography, luminizing, radioisotope production, well logging, accelerator operation, and all other industrial uses. For the three previous periods the exposure of workers in educational establishments and tertiary education was included within the general category of industrial uses; in this Annex these exposures are included within a miscellaneous category in Chapter VII.

196. Differences may exist in the procedures used in various countries to group workers occupationally, which 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 can be made between countries 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 doses assigned for lost dosimeters. These differences and their implications for the validity of comparisons between data were discussed in Chapter I. The approaches used in measuring and reporting occupational exposures in each of the countries for which data were reported are summarized in Table 2. Where important differences in approach are apparent, caution should be exercised in making direct comparisons between data.

197. National data on occupational exposures arising from the industrial use of radiation for the categories mentioned above are given in Table 22. From the data set available, worldwide extrapolations were possible only for industrial radiography and radioisotope production. These were derived using extrapolations within regions based on GDP, using the procedure described in Section I.E. The degree of extrapolation needed varied, and while there was a general correlation with GDP, this was less robust than for the data on medical uses (see Figure XI). The reported data, broken down by practice and region, are given in Table 23. 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 24. Worldwide estimates of exposure were derived using extrapolations within regions, as above, but the data from the United States were limited and the correlation with GDP was poor. The Committee therefore used OECD figures as a surrogate, as was done for exposures from medical uses.

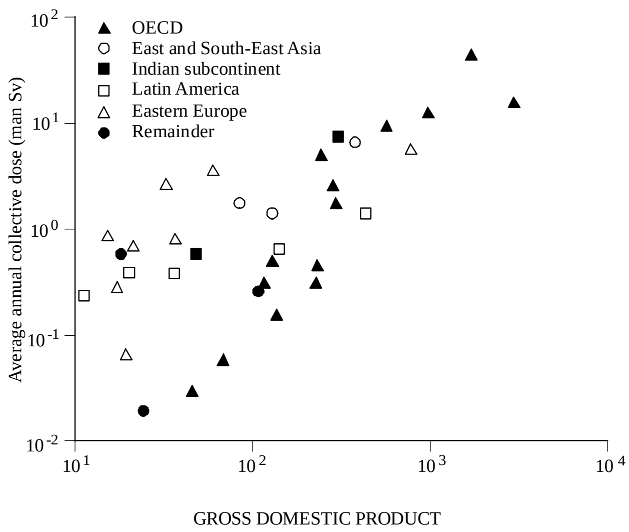

Figure XI. Correlation of collective dose with GDP for industrial uses of radiation.

A. INDUSTRIAL IRRADIATION

198. There are currently 160 gamma-irradiation facilities and over 600 electron-beam facilities in operation throughout the world [I3]. The most widespread uses of these facilities are the sterilization of medical and pharmaceutical products, the preservation of foodstuffs, polymer synthesis and modification, and the eradication of insect infestation. Gamma and electron irradiation facilities have to be constructed such that during normal use any radiation exposure of workers will be very slight. 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 petabequerel (PBq) range; some ^{137}Cs sources are also used. Dose rates in the irradiation chamber would be of the order of 1 Gy s^{-1}, and in some cases there is a need to protect against radiogenic heating that could cause fires.

199. Clearly, because such high dose rates are involved there is a need for sophisticated engineered safety systems that meet the defence-in-depth principle [I3, I8]. The shielding provided by such facilities is necessarily significant, and during normal usage the exposure of workers should be very low. However, significant exposure may result from loss of control over, or damage to, the radiation source, and in extreme cases, the exposures may be sufficient to cause serious injury or even fatalities in the short term. Accidents at these facilities are discussed in Chapter VII.

200. This category of work was not specifically considered in the previous UNSCEAR Survey of Occupational Radiation Exposures [U3]. The available data, given in Table 22, are limited and cover just 15 countries. Of crucial importance is the fact that there are few data from the large industrialized countries, where the greatest number of irradiators are located. Typically, the number of workers in an irradiation facility is relatively small, although the data from Japan indicate a remarkably large number of monitored workers, some 55,000. This accounts for 96% of all the reported monitored workers, and therefore any comparisons should be treated with caution. The data set was not sufficient to allow a reliable worldwide estimate. However, a crude estimate based on a global GDP extrapolation would indicate a monitored workforce of a few hundred thousand and an annual collective effective dose of a few tens of man sieverts worldwide. Thus, the lack of data for this sector is unlikely to affect overall industrial use estimates.

201. For the reported data, the average annual individual effective dose per monitored worker ranges from zero to 1.3 mSv, with an overall average of 0.10 mSv. The corresponding figures for measurably exposed workers range from 0.15 to 2.8 mSv. The latter figure is from Japan and dominates the average annual effective dose to measurably exposed workers, 2.3 mSv. The values of NR for Japan (and overall) are low, indicating that few workers receive any significant exposure. The corresponding values of SR show a significant component of collective dose in the upper levels of individual dose. The raw data for SR_{15} and NR_{15} indicate that, distributed reasonably uniformly over the five-year period, an aggregate of 268 workers received 10.6 man Sv, equivalent to some 50 persons each receiving 40 mSv.

B. INDUSTRIAL RADIOGRAPHY

202. Industrial radiography is performed under two quite different sets of conditions. 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, the radiography is carried out at multiple locations in the field, in which case the radiographic equipment is brought to the location where the radiograph is required, often referred to as site radiography. There are often significant differences in the degree of control that can be exercised in the two situations. However, few of the data reported to the Committee distinguish between the two situations.

203. Both x-ray equipment and sealed sources are used in industrial radiography. The most common sealed sources are ^{192}Ir (activity between 1.8 and 4.4 TBq), ^{60}Co (activity of the order of 0.3 GBq), and ^{137}Cs (activity between 0.3 and 80 GBq). These can be used in three basic formats. The oldest format is direct manual manipulation, which either uses handling equipment or is an integral part of a shielded “torch”. This format, which was prevalent in the 1970s but declining in the 1980s, still has some usage. 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 declining in usage. 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 10 or so 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. Some installed systems use pneumatic or electrical drives. 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.

204. In site radiography, the working conditions are such that some routine exposure is expected. For gamma radiography this mostly derives from exposure while the source is in transit from the shielded container to and from the collimator position; hence, positioning of the control position is relevant. If a collimator is not used, doses from primary radiation and scattered radiation will be larger.

205. In fixed radiography facilities, the shielding and engineered safety systems should ensure low doses. However, variable standards of design for safety systems, or poor maintenance and degradation of the systems, may give rise to incidents that, if not quickly recognized, can lead to exposures above the dose limit or even the levels that might result in deterministic effects.

206. Site radiography presents a number of radiological safety challenges. The work is often undertaken in remote, difficult, or even hostile environments; in addition, supervision tends to be poor, it is a highly competitive business, and the equipment must be robust. A common failure mode in gamma radiography is for the source to become detached from the drive cable but not to be detected immediately, owing to poor or non-existent monitoring. In short, in addition to the possibility of high routine doses, there is the possibility of equipment and procedural failures, a potentially lethal combination. Once sources are removed from control or discarded, they can be the cause of accidental exposures of members of the public (see Chapter VII).

207. Worldwide levels of dose have been estimated from national data by extrapolation within regions based on GDP. The countries reporting data accounted for about 35% of the worldwide total in the first five-year period, increasing to 65% in the third and 66% in the fourth. On average, therefore, the reported data have been scaled upward by a factor of about 2 but with considerable variation about this average for particular periods and regions. The superficial similarity in the percentage of countries reporting for the third and fourth periods warrants closer examination. While there is generally reasonable correlation of the data with GDP, the data for the United States in the fourth period are radically different from the data for the third; 10,000 monitored workers with an annual collective dose of 5.75 man Sv and 274,000 monitored workers with a collective dose of 101 man Sv, respectively. The estimates of numbers of workers and doses in industrial radiography worldwide are given in Table 22, with trends over time also shown in Table 25 and Figure XII. The annual number of monitored workers in industrial radiography, averaged over five-year periods is estimated to have increased from about 70,000 over the first period to about 110,000 over each of the last three periods, with some 10% variation about this value. The average annual collective effective dose is estimated to have increased from about 190 man Sv in the first period to about 230 man Sv in the second, then to have decreased to 160 and 170 man Sv in the third and fourth periods. For the first three periods, about 50% of the collective dose was estimated to have occurred in the countries of the OECD, with about a further 25% to 30% in eastern Europe. For the fourth period the contribution from the OECD countries dropped to 40%.

208. The worldwide annual effective dose to monitored workers averaged over five-year periods fell progressively, from about 2.6 mSv in the first period to 1.4 mSv in the third. However, for the fourth period there was a small increase, to 1.6 mSv. The validity of this figure is confounded by the sparse data from the United States. If it is assumed, as was done elsewhere in this Annex, that the United States approximates to the rest of the OECD, the corresponding figure would be 1.4 mSv, identical to that for the third period. The implication is that at best the worldwide value for the annual effective dose to monitored workers is not falling. The national data show great variability, with some countries showing reductions and others showing increases. Many countries show dose distributions with low values for NR but with relatively high values for SR_{15} and SR_{10}. As with well logging, these ratios suggest that a small percentage of the workforce

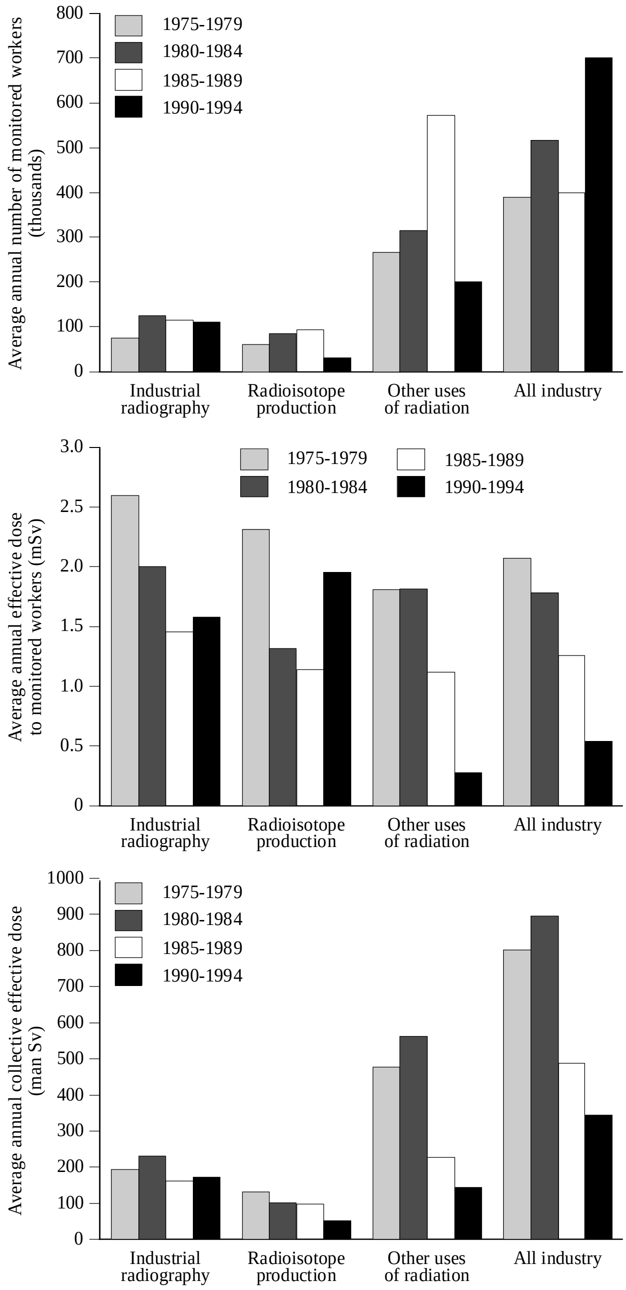

Figure XII. Trends in numbers of monitored workers, doses to workers, and collective doses for industrial uses of radiation.

receives doses, often routinely, above 10 mSv or 15 mSv. These individuals are likely to be involved in site radiography. At a national level the profile of doses can be significantly affected by industrial/commercial activity profiles. For example, large investments in power stations (particularly nuclear), pipeline construction, and the petrochemical industry can result in increased demands for site radiography, which non-destructive testing companies respond to with increased staff and activity; this activity tapers off when industrial investment starts to languish.

209. In previous periods relatively few data were available on average doses to measurably exposed workers as opposed to monitored workers, and no attempts were made to estimate a worldwide average. However, more relevant data have been provided for the fourth period, and the worldwide average annual dose to measurably exposed workers is estimated to be 3.2 mSv. This estimate should be treated with caution as the national data in Table 22 show considerable variation up to about 20 mSv.

210. Dose information for industrial radiographers in the United Kingdom from 1986 to 1994 is given in Table 26 [H1, H2]. This shows that, contrary to the trends for other groups of workers, there has been little or no reduction in the number of workers exceeding specified dose levels. Indeed in the latter part of the reporting period and subsequently, industrial radiography replaced the nuclear industry as the industry with the most exposures in the dose ranges above 20 and 50 mSv.

C. LUMINIZING

211. Radioactive materials have been used in luminizing for decades. The number of workers involved has been low, with fewer than 1,000 reported in each of the periods. There has with time been a shift away from the use of radium to tritium and, to a lesser extent, ^{147}Pm. Tritium is used in two forms: mixed with a phosphor in a paint and as a gas enclosed in a phosphor-lined, glass-walled tube.

212. The data for 1990–1994 reported in Table 22 come from only three countries and are not comprehensive enough to enable a reliable estimate of the worldwide levels of dose from the industry. The reported number of monitored workers is less than 100; they received a collective dose of 0.03 man Sv and an average annual dose of 0.38 mSv. The figures reported for the preceding period were 540 monitored workers, a collective dose of 1.45 man Sv, and an average annual dose of 2.7 mSv. Historically, the doses to workers involved in luminizing were high, but recent years have seen a significant reduction. Indeed it now seems likely that, worldwide, fewer than 1,000 workers are involved and that luminizing contributes less than 1 man Sv to worldwide occupational exposure. It may therefore not be relevant to treat these as a separate category in future reviews but to include them instead in the “other industrial uses” category.

213. Luminizing is one of the oldest industrial uses of ionizing radiation, and while direct occupational exposure may be low, there are other exposures from the legacy of this type of work. The limited controls in place during the early widespread use of radium have left many contaminated sites around the world, some known and others just coming to light. The decontamination and remediation of these sites have implications for occupational exposure, but the data are very scarce and are likely to be subsumed in broader categories. Another aspect of luminizing is the fact that there are many millions of luminized items that can end up in the public domain.

D. RADIOISOTOPE PRODUCTION AND DISTRIBUTION

214. Radioisotopes are produced for a great variety of industrial and medical purposes. The main source of occupational exposure in radioiosotope production and distribution is external irradiation; internal exposure may be significant in some cases, and arrangements are then made for personal monitoring. 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 (e.g. 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.

215. Worldwide levels of exposure have been estimated from reported national data, using extrapolation within regions based on GDP. The data set is smaller than that for industrial radiography, and on average the scale factor used is higher, about 3, with considerable variation about this figure. Nevertheless, it has been possible to make an estimate of worldwide exposure. The number of workers involved in radioisotope production around the world, averaged over five-year periods, increased from about 57,000 in the first period to about 88,000 in the third period, reflecting the growing use of radioisotopes in both industry and medicine. However, the estimate for the fourth period is only about 24,000 workers monitored. Data for previous periods was dominated by data from the United States (about 30,000 monitored in the third period). There are no signs that the market for radioisotopes is declining, and even if the United States’ contribution in the fourth period was the same as in the third, the number of monitored workers would still be only 50,000. It is therefore concluded that there has been a genuine reduction in monitored workers. The industry is now mature and well established, with multinational companies replacing the often nationally focused entities that prevailed in earlier years. This has meant some

rationalization of production and economies of scale, reflected in the declining numbers of exposed workers.

216. Despite the above-mentioned increases over the first three periods, the estimated worldwide annual collective effective dose dropped from more than 130 man Sv in the first period to about 100 man Sv in both the second and third. The estimate for the fourth period is 47 man Sv, a reduction by a factor of about 2. While the estimated value may be low as the result of a smaller data set, when the error margins over time are taken into account, the data would be consistent with a compound reduction of 30% per period. Alternatively, the reduction by a factor of 2 relative to the last period would be consistent with the emphasis given to ALARA in the late 1980s by international bodies [E3, I5, I12] having worked its way through to implementation in the fourth period. Overall, the estimated value is considered valid. As in previous periods, about two thirds of these collective doses are estimated to have occurred in OECD countries, with most of the remainder occurring in eastern Europe and southern and South-East Asia.

217. The annual dose to monitored workers worldwide averaged over five-year periods fell, from about 2.3 mSv in the first period to about 1.1 mSv in the third period. The estimate for the fourth period, 1.9 mSv, indicates a reversal of this trend. While the limited data set must cast some doubt on this figure, it would be consistent with the significant reduction in the estimated workforce. More data were available for the fourth period on average annual doses to measurably exposed workers, allowing a worldwide estimate of 2.9 mSv. Some two thirds of the monitored workers are estimated to have received measurable doses. This is a fairly consistent pattern across the reporting countries, and the dose profiles indicated by the NR and SR values are similar to those for industrial radiography.

218. In the manufacture and processing of radionuclides there is the potential for both internal and external exposure. It is not always apparent, however, from the reported data whether the internal component was significant and whether it was included in the dose estimates. The data for the United Kingdom from 1985 and for Finland from 1987 onward include doses from intakes of radionuclides. In general, the contribution to the total dose was reported to be a few percent. It would be useful if in future all data could clarify the component parts.

E. WELL LOGGING

219. Well logging has been identified in some countries as an industrial use 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, such as on oil rigs. Both gamma and neutron sources are used in well logging, but the contribution from each to the reported doses is generally not indicated.

220. The data on well logging, presented in Table 22, are not sufficient to enable a reliable estimate of worldwide levels of dose. Nevertheless, a review of the data suggests that a scaling factor of 10 used on the total reported data could set an upper bound for the likely worldwide figures. This suggests a worldwide annual collective effective dose of a few tens of man sieverts, or less than 10% of the overall exposure from industrial uses.

221. The annual effective dose to monitored workers averaged over the reported data for 1990–1994 is 0.36 mSv, continuing the trend observed over the three previous periods, for which the corresponding figures were 1.3, 1.2, and 1.1 mSv. Although this is a relatively low figure, there was considerable variation between countries; Slovakia, for example, reported a value of 5.3 mSv. The average annual effective dose to measurably exposed workers based on the aggregated reported data was 0.79 mSv for the fourth period. The distribution ratios NR and SR indicate that while a majority of monitored workers get low doses, some in this industrial sector receive more significant doses, although not as high as in, for example, industrial radiography or radioisotope production.

F. ACCELERATOR OPERATION

222. Consideration is limited here to occupational exposures arising from accelerators used for nuclear physics research at universities and 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 them 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 from accelerators result from induced radioactivity and occur mainly during the repair, maintenance, and modification of equipment. They come 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 from external irradiation.

223. 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 typical annual collective doses per accelerator were 1–2 man Sv before 1960; this is still true for many of the early cyclotrons that are still in operation. Between 1960 and 1980, beam extraction techniques were improved, which led to reduced levels of activation products; these reductions were, however, largely offset by the continuing increases in beam power.

224. 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 exposures during maintenance.

225. As a consequence of these technical developments and the greater emphasis given generally to ALARA programmes at accelerators, there were large reductions in the collective effective doses at large accelerator laboratories between the mid-1970s and the mid-1980s [P2]. Decreases in the annual collective dose, from about 0.1 to 0.01 man Sv, were experienced at Deutches Elektronen Synchrotron; from about 0.2 to 0.02 man Sv at Daresbury Nuclear Physics Laboratory; from about 5 to 1.5 man Sv at the European Organization for Nuclear Research; and from about 0.5 to about 0.2 man Sv at the Lawrence Berkeley Laboratory.

226. The available data, shown in Table 22, cover only some 1,300 monitored workers from eight countries and are not complete enough to permit a reliable estimate of the worldwide dose from accelerators; however, the sums (or averages) of the available data are shown. The average annual collective effective dose for the reported data is about 1.0 man Sv, compared with about 7.4 man Sv for the first period and 3.7 and 3.5 man Sv for the intervening periods. The data set does not permit drawing any conclusions beyond that the levels of annual collective dose are consistent and that the contribution to worldwide doses from all industrial uses is likely to be insignificant. The average annual effective dose to monitored workers for the reported data is 0.75 mSv, slightly higher than the 0.62 mSv reported for the previous period. Again, undue significance should not be attached to this apparent increase, and it would be more appropriate to conclude that the data are broadly consistent with those for previous periods.

G. ALL OTHER INDUSTRIAL USES

227. There are many other uses of radiation in industry, e.g. in soil moisture gauges, thickness gauges, and x-ray diffraction, but occupational exposure data for these are not, in general, separately identified or reported. 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 Chapter. The average exposure levels of workers involved in other uses of radiation are, in general, small. However, because of the way in which the doses are aggregated, they may disguise somewhat higher average doses in particular occupations. The only way to ascertain the existence of occupations, or subgroups within occupations, receiving doses significantly in excess of the average is for those who compile data to inspect the data periodically. Such inspection is to be encouraged.

228. As is the case for the comparable general category under medical uses, there are several entries of tens of thousands of monitored workers, e.g. in Germany, Japan, and the United Kingdom. These entries appear in this Section because the national systems for collecting data do not readily permit desegregating the data into the categories used in this review. Nevertheless it is important that these data are captured as they feed into the next Section.

H. SUMMARY

229. Table 24 shows the national data from all industrial uses of radiation grouped together. The data are more complete than for the separate categories of industrial use of radiation, but as with the data for medical uses they suffer from limited data from the United States, which is important in the estimation of worldwide exposure. While the normal method of regional extrapolation based on GDP (as outlined in Section I.E) was considered acceptable for estimating worldwide industrial radiography and radioisotope production, its validity was dubious when applied to all industrial uses. The total reported data for the United States during 1990–1994 covered some 10,000 monitored workers who experienced an annual collective effective dose of 25 man Sv. The corresponding figures for 1985–1989 were 274,000 monitored workers and 150 man Sv. While some reductions may have occurred, they are extremely unlikely to have been this large.

230. The Committee considered alternative methods of estimating the values for the United States. The region with the most similarities to the United States is the rest of the OECD countries. The UNSCEAR 1993 Report [U3] showed the collective effective dose per unit GDP (man Sv per 10^{12} United States dollars) for the United States divided by that for the rest of the OECD to be within 10% of 2.0 for each of the earlier periods. Given that the ratio of the GDPs for 1990–1994 is approximately the inverse of this, namely 0.5, it appears reasonable to carry out extrapolations of world estimates on the basis that the figures for United States can be taken to be equal to the figures for the rest of the OECD. World estimates using this approach are given in Tables 25 and 27. For comparison, world estimates based on the method in Section I.E are given in brackets in these tables. It is important to note a significant difference between the data quoted for the first three periods in Tables 25 and 27. The UNSCEAR 1993 Report included exposures to people involved in education under industrial uses, whereas this Annex treats education separately. Table 25 summarizes worldwide exposure, by practice, from industrial uses, and for the first three periods it was easy to recalculate the data

without the contribution from education, permitting a suitable comparison with the data for 1990–1994. However, for Table 27, which summarizes the contribution of the different regions, such readjustments are not readily achievable because of the way earlier data were configured. The worldwide totals for the first three periods include a contribution from education and are therefore different from those quoted in Table 25. Thus caution needs to be exercised in comparing data over the various periods.

231. Using data adjusted for the non-inclusion of educational uses, the annual number of monitored workers involved with industrial uses of radiation, averaged over five-year periods, is estimated to have been 390,000, 510,000, 400,000, and 700,000 from the first to the fourth periods. The uncertainty associated with these figures does not allow inferring a clear upward trend; however, such a trend would be consistent with increased global industrialization. Even so, in each of the periods the OECD (including the United States) accounts for a vast majority of the exposed workers. The average annual collective doses, after an initial rise from 800 to 900 man Sv over the first two periods, dropped to 490 and then 360 man Sv in the third and fourth periods, respectively. In general, some three quarters of the dose comes from OECD countries.

232. The annual effective dose to monitored workers averaged over five-year periods fell consistently over the four periods, with values of 2.1, 1.8, 1.2, and 0.51 mSv (in chronological order). This downward trend is evident for most countries and regional groupings, but there is considerable variation. For the last period, data were available on the average annual effective dose to measurably exposed workers, giving a worldwide value of 2.2 mSv. This is greater by a factor of 4.5 than the value for monitored workers. This factor is larger than that for reactor workers or medical workers and is perhaps indicative of better defined subgroups of workers, particularly in industrial radiography and well logging, who can routinely receive higher exposures.

233. While the confounding factor of educational uses means that care must be exercised when comparing the data in Table 27 between periods, it is instructive to look at the normalized collective dose values in man Sv per 10^{12} United States dollars. Although there are region-to-region variations in the magnitude of the change, there is a consistent general downward trend. The worldwide values were 120, 72, and about 30 man Sv per 10^{12} United States dollars in the first, second, and combined third and fourth periods, respectively.

V. NATURAL SOURCES OF RADIATION

234. Since natural radiation is ubiquitous it is necessary to direct attention to the highest exposures and to those cases where actions to reduce or limit exposures are most likely to be effective. Enhanced levels of natural background radiation are encountered in many occupational settings, especially underground mines. Mining involves a large number of workers, and although data are more limited than those for occupational exposures to man-made sources, the annual collective effective dose has been estimated to be twice as large [U3]. There is less awareness of exposures from natural radiation in other settings, and often there are no regulatory requirements to monitor and record these occupational exposures. Consequently, surveys are necessary at the national level to determine the scale and nature of the exposures. A general review of exposures from natural sources of radiation is given in Annex B, "*Exposures from natural radiation sources*". The UNSCEAR Survey of Occupational Radiation Exposures specifically sought information on exposures of aircrew to cosmic rays; exposures of coal miners, primarily to radon decay products; and exposures of miners of minerals other than coal. Significant individual exposures to radon decay products can also occur in other workplaces, and there may also be significant exposures to long-lived natural radionuclides in dusts during the handling and processing of bulk quantities of minerals and other materials. Uranium mining is not considered here but is included instead as part of the nuclear fuel cycle (Chapter II).

A. COSMIC-RAY EXPOSURES TO AIRCREW

235. In the course of their work, aircrew and others who fly frequently are exposed to elevated levels of cosmic radiation of galactic and solar origin and secondary radiation produced in the atmosphere, aircraft structure, etc. This has been recognized for some time, and the exposure of aircrew was estimated in the UNSCEAR 1993 Report [U3]. The growing interest in these exposures in recent years is due to three considerations. The first is that the relative biological effectiveness of the neutron component of aircrew exposure was being underestimated by the definition of the quantity tissue dose equivalent and by the specification of a quality factor [I19, N1]. Secondly, subsonic commercial aircraft, particularly business jet aircraft, can attain higher altitudes [W2]. Finally, ICRP recommended in its Publication 60 [I12] that the exposure of aircrew in jet aircraft should be treated as occupational exposure. Particularly worthy of note is the study of the European Dosimetry Group (EURADOS) [E1], which reviewed the data on exposure of aircrew to cosmic radiation in response to the ICRP recommendations.

236. Dose rates from cosmic radiation vary with altitude, latitude, and phase of the solar cycle. For subsonic flights at altitudes up to 13 km, the dose equivalent rates increase as a function of altitude and latitude. Available measurements were compiled in the review cited above [E1], and a figure

illustrating the results is included in Figure III of Annex B, "*Exposures from natural radiation sources*". The data are given in the previous quantities; it is estimated that effective doses calculated using the new quality factors from the ICRP recommendations [I12] would be similar. The UNSCEAR 1993 Report [U3] gave the results of a worldwide measurement programme on Lufthansa airplanes. Most flight altitudes were in the range 10 to 11.9 km, where effective dose equivalent rates were less than 5 μSv h^{-1} and 8 μSv h^{-1}, respectively. These values are roughly in agreement with current estimates. The more recent review of the exposure of aircrew [E1] indicates that the effective dose rate at an altitude of 8 km in temperate latitudes is typically up to about 3 μSv h^{-1}. At 12 km, the value would be about twice this. These values may be compared with those given in Annex B, "*Exposures from natural radiation sources*". The equivalent dose rates were noted to be highly dependent on the flight profile, ranging from 0.2 μSv h^{-1} for a flight of 0.4 hours at a cruising altitude of 3.6 km to 5.8 μSv h^{-1} for an Athens-New York flight of 9.4 hours at a mean altitude of 12 km [O6].

237. The following broad conclusions have been drawn from the data from measurements and evaluations of exposures at aircraft altitudes [E1]:

(a) location within an aircraft does not affect the exposure level by more than ±10%;
(b) going from the equator to either pole, the dose rate increases up to a latitude of about 50° and remains approximately constant at higher latitudes. The increase is greater for the high-LET component (a factor of 3 to 5) than for the low-LET component (a factor of 1.5 to 2.5);
(c) the total dose equivalent rates increase with flight altitude for all latitudes;
(d) values of the total dose equivalent correlate well with the variation in cosmic radiation intensity due to the solar cycle of about 11 years, being higher at times of minimum solar activity and vice versa; the values range from about 0.8 to 1.2 of the mean; and
(e) the relative contributions of the high- and low-LET components of the dose equivalent are broadly similar at temperate latitudes and at normal flight altitudes.

238. Drawing on the measurements and evaluation of the EU research programme [B5, E1, O7, S5, T1], for flights at temperate latitudes at a typical altitude of 10.6 km (35,000 ft) and for average solar activity, it can be estimated that a total time at altitude of about 200 hours is needed to accumulate 1 mSv. Near the equator and at this altitude, the time needed is about 400 hours. At an altitude of 11.8 km (39,000 ft) these times are 150 and 300 hours, respectively, and at an altitude of 10 km (33,000 ft) 250 and 500 hours. If it becomes necessary to assess individual doses, this may be done by combining roster information with "route doses". Route doses may be measured or calculated using computer programs developed for this purpose for particular routes and flight profiles. For example, a flight from northern Europe to the eastern seaboard of the United States, a flight time of about 7 hours will result in an effective dose between 30 and 40 μSv. For a longer flight, say from northern Europe to Japan, the total effective dose is about 50 to 70 μSv. Transatlantic flights at the altitudes used by supersonic aircraft give effective doses similar to those for subsonic aircraft, the higher dose rates being offset by the shorter flight times. Estimates of effective dose from cosmic radiation for typical flight routes are given in Table 28.

239. The data on occupational exposures in civilian aviation from the UNSCEAR Survey of Occupational Radiation Exposures are given in Table 29. Only three countries, Bulgaria, Finland, and the United Kingdom reported data, and in each case without any dose distribution ratios. Of these, the United Kingdom has the most extensive air transport industry, and it is useful to look in more detail at the derivation of the United Kingdom submission. Available data indicate that aircrew on long-haul flights may be airborne for 600 hours in a year [D1], during which they are estimated to receive an annual effective dose of 3 mSv [H3]. To take account of short-haul flights as well, an annual average of 500 hours aloft was assumed in deriving the average annual effective dose of 2 mSv and the collective effective dose of 50 man Sv given in Table 29. In the UNSCEAR 1993 Report [U3], an annual flying time of 600 hours was estimated for aircrew in some European countries and about a 50% longer flying time in the United States. Based on an average annual effective dose equivalent of 3 mSv to about a quarter of a million aircrew worldwide (appropriate for the late 1980s), an annual collective effective dose equivalent for all aircrew of 800 man Sv was calculated. From the data available there would appear to be no substantive change to any of these parameters, so this estimate can be taken to apply also to 1990–1994. A number of subgroups and situations deserve mention and are discussed below.

240. The doses to other persons, such as couriers, is much more difficult to estimate. Based on an analysis carried out at London airport [G1], it was determined that some professional couriers undertook 200 journeys a year, implying 1,200 flying hours and an annual effective dose of 6–10 mSv. The number of such individuals is unknown, but the annual collective effective dose must be a small fraction of that to aircrew. In Germany, approximately 20,000 persons other than aircrew who are frequent flyers are estimated to receive annual doses above 1 mSv [S2].

241. The Concorde carries an in-flight warning meter, and this has permitted the accumulation of a large amount of data on exposure at typical supersonic flight altitudes. The average total dose equivalent rate in 1976–1983 was 11.2 μSv h^{-1}; average values reported for 1988, 1989, and 1990 were 12.2, 11.6, and 10 μSv h^{-1}, respectively, for altitudes of about 18 km [D1]. Values measured by Soviet scientists in 1977 for supersonic aircraft, ranging from 10 to 12 μSv h^{-1}, agree with these values [A1]. The relative contributions of both components are about the same as for subsonic flight altitudes. While the crew of supersonic aircraft such as the Concorde are subject to the highest dose rates experienced in civil aviation, such crew do not

necessarily receive the highest doses. British Airways data for Concorde flight crew in 1994 indicated an average duty time of 382 hours in 12 months, and for the subgroup with the longest flight time, engineers, the average duty time was 403 hours [E1]. Thus, average annual effective doses to aircrew would be about 3 mSv.

242. Elevated exposure rates may be associated with solar flare events. At maximum solar activity, several dozen flares may be observed in one day. However, only a small fraction of flares (about 3%) produce high-energy fluences, and only a small fraction of these cause increased intensity of cosmic radiation [L1, W1]. In years of minimum solar activity, on average only one significant event in a year is observed. The largest events take place at the end of the period of maximum solar activity. The rise in dose rates associated with a flare is quite rapid, usually a matter of minutes, and the duration may be hours or longer. The influence of solar flares on the radiation situation at the altitude of air transport has been thoroughly reviewed [F1]. It was found that the upper limit of the dose equivalent rate during the February 1956 flare was about 30 mSv h^{-1} at 20 km altitude and 10 mSv h^{-1} at 10 km. That flare was the most important of known events, and since then dose rates associated with flares have been very much smaller. O'Brien [O1] calculated the additional contribution to dose equivalent for regular polar flights over the period February 1984 to July 1992, during which 14 periods of energetic solar activity were observed. At 12 km, the additional contribution to the dose equivalent was calculated to be 3% and at 18 km, 7%. In 1993, a year of medium solar activity, the maximum annual effective dose to an individual on Lufthansa flights across the North Atlantic was estimated to be 4.5 mSv [S2]. Altogether, 25,000 persons work as flight personnel in Germany. Most of them are estimated to be exposed to annual doses of 1–6 mSv. For a relatively small number of persons (of the order of 100), annual exposures above 6 mSv are estimated to occur at times of low solar activity on some routes (high geomagnetic latitude and high altitude). Exposure during space flight was reviewed in the UNSCEAR 1993 Report [U3]. Some further information on exposure in space flight is given in the Proceedings of the International Workshop on Space Radiation Damage and Biodosimetry, held at Houston, Texas, in September 1996 [C8]. One paper reviewed the sources of charged-particle radiation that contribute to radiation exposure on manned spacecraft and provided estimates of the dose rate expected for the International Space Station; these estimates are based on measurements made on the Mir orbital station [B4]. Another paper presented the result of a biodosimetry analysis for the space flight Mir-18 using fluorescence *in situ* hybridization (FISH) techniques [Y1].

243. In summary, the data indicate that the average annual effective dose to aircrew is typically 1–2 mSv for those on short-haul flights and 3–5 mSv for those on long-haul flights. Few aircrew will exceed these values because there are laws regulating flying hours. A separate group, couriers, may spend more time in flight over a year but even so are unlikely to exceed 10 mSv. Worldwide annual collective effective dose to aircrew from cosmic ray exposure is estimated to be 800 man Sv. This estimate is based on the extrapolation of limited data, and there is a need to extend the data for future assessments. There are now good data on typical exposure rates and computer programmes that account for a range of variables and allow reasonable estimates of route doses. Also, for legal reasons logs are kept of the hours and routes flown. Bringing these two data sets together should in the future allow much better estimates of dose profiles. This matter has been given impetus by the ICRP recommendation that exposure of aircrew be treated as occupational exposure [I12], and the subsequent inclusion in both the IAEA [I5] and the European Union [E3] Basic Safety Standards.

B. RADON EXPOSURES IN WORKPLACES

244. The main source of exposure in most mining operations is radon. Since radon is also important in other workplaces, it is convenient to specifically consider exposure to it in the workplace. Exposure to long-lived radionuclides in mineral dusts can, however, be important in certain mining and other situations, and these will be discussed below.

245. Several isotopes of radon exist in nature, but one, ^{222}Rn, dominates in terms of the dose to workers. Under some circumstances, ^{220}Rn (commonly known as thoron because it is in the ^{232}Th decay chain) may also be important. For convenience, unless otherwise stated, 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 quoted. Workplaces themselves are often categorized as being either below ground or above ground. The main below-ground workplaces are mines, but there are also radon spas [S3], subways, show caves and tourist mines, and underground water treatment works and stores. Above-ground workplaces include factories, shops, offices, and schools. In the UNSCEAR 1993 Report [U3], only the exposure to radon progeny in underground mines was considered.

246. The levels of radon in workplaces are exceptionally variable, and high doses to workers can arise in places other than uranium mines. It is generally accepted that it would be unreasonable on the grounds of cost to consider controlling the normal ambient levels of radon in workplaces. These levels are therefore usually regarded as essentially unamenable to control. However, in recent years there has been increasing interest in those workplaces, including mines, where levels are high and there is some scope for reducing them. The approach adopted by ICRP [I12] is that the regulatory agency should identify the workplaces that warrant control. This necessitates surveys to determine the range of exposures, and it is clear that many countries have yet to complete such surveys and to determine where controls should be applied. The special quantities and units that are used to characterize the concentration of radon progeny in the workplace and the exposure of workers to them are discussed in Chapter I.

1. Underground mining

247. Mining is an extensive industry. In 1991, there were an estimated 4.7 million underground miners worldwide (see Table 30), about 84% of them engaged in coal mining and the remainder engaged in mining other minerals [C4]. In the latter group are about 90,000 persons engaged in the mining of uranium ores. China is the largest employer of workers in coal mines, and South Africa of workers in other mines (mainly gold mines). These numbers fluctuate from year to year with changing economic conditions. The exposure to radon progeny depends on a number of factors, including the type of mine, the geology, and the working conditions, particularly the ventilation. Available data from the UNSCEAR Survey of Occupational Radiation Exposures to miners are included in Table 29. Exposures to natural sources of radiation arising from mining have received much less attention than those arising from the industrial and medical uses of man-made sources of radiation. Relatively few data are available for the period of interest, and their quality or reliability is generally much lower than for the data reported elsewhere in this Annex for other occupations. This is a consequence of the paucity of the data as well as the fact that many were derived from environmental, as opposed to personal, dosimetry; dose estimates are subject to considerable error when they are based on grab samples of air instead of personal air samplers. This situation is changing, however, and more comprehensive and reliable data can be expected in the future.

248. In 1991, there were about 50,000 underground coal miners in the United Kingdom. In general, the exposure of coal miners to radon is low because good ventilation is required. The average effective dose to coal miners from radon was 0.6 mSv in that year, with about 70 miners receiving more than 5 mSv and 10 of them more than 15 mSv [H3]. The total collective dose from radon to coal miners was estimated to be 28.6 man Sv. A survey of non-coal mines (tin, gypsum, potash, etc.) that covered about 1,300 miners indicated an average annual effective dose of 4.5 mSv, with about 330 exceeding 5 mSv, of whom 240 exceeded 15 mSv and 3 exceeded 50 mSv [H3]. The total collective effective dose from radon to the non-coal miners in the United Kingdom was estimated to be about 6.1 man Sv.

249. The exposure of workers in South African gold mines is generally low, but the size of the workforce is substantial [W4]. In the mid-1990s, the annual production from 40 mines was about 100 Mt of ore and 600 t of gold. About 2,000 t of U_3O_8 is produced as a by-product from three of the mines. The average number of employees in the gold mines, including contractors, was about 310,000, about 250,000 of whom worked underground. The mean depth of the workings is 1,600 m, and the maximum is about 3,500 m. Such depths require a substantial throughput of cooled air to maintain an acceptable working environment, which is the reason why radon progeny concentrations are generally low. In surveys conducted between 1989 and 1991, it was found that 97% of the workers were exposed to less than 1,100 Bq m^{-3} (0.3 WL) and that no workers were exposed to more than 3,700 Bq m^{-3} (1 WL) [W3]. Since then, another survey was carried out in 1992 and 1993 in 21 of the mines; that survey covered 60% of the total underground workforce [W4]. The average concentration of nearly 2,000 measurements was 190 Bq m^{-3}, and 96.7% of the readings were below 1,100 Bq m^{-3}. The maximum was 3,300 Bq m^{-3}. Gamma dose rates and exposure to long-lived radionuclides in ore dusts were also measured. Effective doses from radon progeny were determined by both individual dosimetry and area measurements; the former gave values that were, on average, about 50% lower than the latter. Doses from radon progeny generally made the main contribution to total effective dose (on average, 1.8 mSv in a year, or 71%), with external gamma radiation representing the next largest component (0.64 mSv in a year, or 25%). Long-lived alpha radiation from ore dust contributes very little to the total effective dose (0.11 mSv in a year, 4%). On the assumption that the value for radon applies to all 40 gold mines, the annual collective effective dose in South African gold mines in the first half of the 1990s would have been 450 man Sv. The total annual collective effective dose from all three sources considered would have been 640 man Sv.

250. In Germany, an estimated 1,000 persons are employed in underground mines (other than uranium or coal mines) that expose them to radon levels between 1,000 and 3,000 Bq m^{-3} [S2]. A further 200 persons are employed in mines where the levels exceed 3,000 Bq m^{-3}. These mines include show caves and tourist mines. A few hundred workers in coal mines are estimated to be exposed to radon concentrations of 1,000–3,000 Bq m^{-3}.

251. The data taken from the UNSCEAR Survey of Occupational Radiation Exposures and reported in Table 29 are limited and on their own not sufficient to allow an estimate of worldwide exposure. Over the years, there have been a number of studies of doses to workers in underground mines; they are summarized in Table 31. The data, which are presented separately for coal mines and other mines (excluding uranium), cover some 1,200 mines. They refer to various time periods, which limits the extent to which they can be evaluated in a coherent manner. Neither the quality nor the extent of the data are considered adequate to allow their use to establish trends in worldwide exposures from underground mining. They have, however, been used to estimate worldwide doses from the inhalation of radon progeny; these are summarized in Table 32. The doses can be considered broadly representative for the early 1990s. They were estimated as the sum, over all the countries, of the products of the number of miners and the reported exposure to radon progeny. The average exposure for those countries reporting data has been assumed to apply worldwide.

252. The worldwide annual collective effective dose from the inhalation of radon progeny in underground mines (excluding uranium mining) is estimated to be about 3,200 man Sv, with about 1,400 man Sv (40%) arising from coal mines and about 1,800 man Sv (60%) from other mines. The comparable figures reported in the UNSCEAR 1993 Report [U3] for 1985–1989, were 5,300 man Sv overall and 1,500 and 3,800 man Sv for coal mining and other mining, respectively. The

drop for 1990–1994 is attributable to two main factors. First, the UNSCEAR 1993 Report [U3] used the ICRP recommended conversion factor of 1 WLM = 5 mSv [I13], as opposed to 1 WLM = 5.6 mSv, which had been used previously. Secondly and more importantly, for the non-coal-mine estimate, the most up-to-date data [W4] have been used for the South African miners. The South African data dominate the non-coal-mining data, and that for the early 1990s (average annual effective dose of 1.8 mSv) is significantly lower than the value of 5.6 mSv derived from data in the 1970s and used in the UNSCEAR 1993 Report [U3].

253. Exposures may also occur from external irradiation and from the inhalation of thoron progeny and of dust containing long-lived alpha emitters of the uranium and thorium series; consequently, the dose estimates in Table 32 from the inhalation of radon progeny alone understate the total dose. Few data are available on these other pathways of exposure, and their relative magnitudes will vary from mine to mine depending on the geology and working conditions. Estimates made for a number of mines in the former USSR [P3] suggest that the contribution from other pathways is about 1 mSv per year, which, except in coal mines, is a small fraction of the dose from radon progeny. This value was used in the UNSCEAR 1993 Report [U3]; however, the value available from the South African survey [W4] is 0.75 mSv. Overall it would seem appropriate to use a value of 0.8 mSv to account for the other pathways. When such an allowance is made, the annual collective effective dose from all exposure pathways for coal mining worldwide would become about 4,500 man Sv and that for other mining (excluding uranium) about 2,400 man Sv. The corresponding average annual effective doses from all pathways would be about 1.2 mSv and 3.2 mSv for coal and other mines, respectively.

254. The doses estimated in the above manner represent exposures received by miners at work in underground mines. They require further correction, however, if they are to be compared directly with exposures arising in other industries, where exposures from natural sources of radiation are not included in the reported doses. Similar correction is needed if the quantity of interest is the additional, rather than the total, dose received while at work. To facilitate fair comparisons with exposures in other industries and to allow the derivation of a quantity that represents the additional exposure from the work, the above annual dose estimates need to be reduced by about 0.5 mSv; this is the annual dose that the worker would otherwise have received if not at work. It is based on 2,000 hours work per year and a worldwide average dose from external irradiation and inhalation of radon progeny of 2.4 mSv (see Annex B, "*Exposures from natural radiation sources*").

255. After correcting for other exposure pathways and for exposures that would have been received irrespective of work, the worldwide annual collective effective dose from underground (non-uranium) mining during the early half of the 1990s is estimated to have been about 4,600 man Sv; about 2,600 man Sv arose in coal mining and 2,000 man Sv arose in other mines (excluding uranium). Of those countries identified separately in Table 32, South Africa (about 39%) makes the largest contribution to the total collective dose, with significant contributions also coming from the former USSR (about 19%) and Poland (about 22%). The additional worldwide average annual effective dose received by underground miners from their work is estimated to have been about 0.7 mSv in coal mines and about 2.7 mSv in other mines (excluding uranium), although there was considerable variation about these averages from country to country and from mine to mine in a given country. Somewhat greater individual and collective doses are likely to have been received in the late 1970s and early 1980s because less attention was paid to the control and reduction of exposures from this source. Insufficient data are available, however, to allow reliably estimating how much greater they might have been; the few data in Table 31 suggest that they may have been substantially greater.

256. Very approximate and tentative estimates were made in the UNSCEAR 1988 Report [U4] of collective doses from natural sources of radiation. For coal mining, an upper estimate of 2,000 man Sv was made for the worldwide annual collective effective dose; this was based solely on exposures in mines in the United Kingdom and on the worldwide production of coal. Given its very approximate nature and the change adopted here in the conversion factor for exposure to radon progeny, the estimate compares favourably with the current estimate of about 2,600 man Sv. A very rough estimate of 20,000 man Sv was also made in the UNSCEAR 1988 Report [U4] for the annual collective effective dose from underground mining apart from coal and uranium; that estimate was based on a very tentative assumption that the arithmetic mean annual individual dose was 10 mSv (from a range of reported values between 0.1 and 200 mSv) and that there were, on average, 500 underground miners (excluding coal and uranium) per million population. This earlier tentative estimate was revised downward to 4,100 man Sv in the UNSCEAR 1993 Report [U3] on the basis of better data. Further improvements in data and changes in the conversion coefficients have allowed a lower estimate for non-coal mines (other than uranium): 2,000 man Sv. The overall estimate for underground mining, 4,600 man Sv, is about two thirds of that for the period 1985–1989.

2. Exposures above ground

257. Exposures to radon progeny may be important in some above-ground workplaces. Radon exposures are largely determined by the geology underlying the building, its construction, and the ventilation. It has been known for some time that high levels of radon exist in some dwellings, but it is only relatively recently that attention has been paid to workplaces other than mines. The spectrum of places where radon can present a hazard is potentially large and includes shops, schools, and offices. Radon entry into buildings is from both diffusion and pressure-driven flow of soil gas through cracks in the floor. The mechanisms of radon entry into buildings are discussed in Annex B, "*Exposures from natural*

radiation sources". Building materials and radon in water may also contribute to the levels of radon in buildings. The experience obtained from studies of radon levels in dwellings may help to identify those workplaces where radon concentrations may exceed any action level specified by the national authority for the purpose of determining whether controls need to be applied. Some countries have used the concept of radon-prone areas, as suggested by ICRP [I13]. These areas can be defined in a number of ways. One way is to define them as areas in which at least 1% of the dwellings have radon levels more than 10 times the national average.

258. In Germany, the number of persons exposed to radon concentrations between 1,000 and 3,000 Bq m^{-3} was estimated to be about 50,000 [S2]. A further 10,000 were estimated to be exposed to a radon concentration of more than 3,000 Bq m^{-3}. These are only crude estimates. Another 2,000 or so persons in working places associated with the water supply industry were estimated to be exposed to radon concentrations between 1,000 and 3,000 Bq m^{-3} and about 300 persons to levels above 3,000 Bq m^{-3}. Elevated levels of radon in above-ground workplaces have been found in a number of countries. Levels above 1,000 Bq m^{-3}, the action level suggested in the international basic safety standards [I5], have been found in some countries, but often the sample sizes were small. In the United Kingdom, radon concentrations were measured in 4,800 workplaces in areas of the country where levels were expected to be above average. The mean concentration was 210 Bq m^{-3}, and in 710 cases the concentration exceeded 400 Bq m^{-3}. Of the estimated 1.7 million workplaces in the United Kingdom, 5,000 workplaces with about 50,000 workers are expected to exceed this level [H3]. Their collective effective doses and average individual doses are 270 man Sv and 5.3 mSv in a year, respectively, with 2,500 or so workers receiving doses exceeding 15 mSv in a year.

259. There are clearly very few data on which to base an estimate of worldwide exposure. However, a crude estimate could be based on the United Kingdom experience. As with underground mining it is necessary to make an adjustment for the general ambient level of exposure to radon. If the same reduction is used, the estimated average annual collective dose to those exposed above the action level would drop to about 240 man Sv in the United Kingdom. If this figure is then extrapolated on the basis of GDP, the worldwide annual collective effective dose would be about 6,000 man Sv. This is clearly very crude, and country-to-country variables such as geology, building materials, configurations, and regulations could have a significant effect. This is an area where more data are needed to help refine the estimates.

C. EXPOSURES IN MINERAL PROCESSING INDUSTRIES

260. The earth's crust generally contains concentrations of uranium of the order of 0.5–5 ppm and of thorium of the order of 2–20 ppm. The average activity concentration of ^{238}U and ^{232}Th are in the range 25–50 Bq kg^{-1} (see Annex B, "*Exposures from natural radiation sources*"). However, both elements may be concentrated in certain rocks by geological processes such as partial melting and recrystallization, which can be caused by the movement of tectonic plates and other processes. Uranium and thorium are sometimes enriched in granites and alkaline igneous rocks, often accompanied by tin and minerals containing rare earth elements. Particularly high concentrations can occur in coarsely crystalline rocks called pegmatites, which are formed during the solidification of the last fraction of molten rock, where relatively high concentrations of less common elements have built up. Uranium is also concentrated in some conglomerates, sandstones, black shales, and phosphorites by sedimentary processes. These sedimentary uranium materials may be mobilized and the uranium concentrated by metamorphic processes to form complex deposits that usually contain ores of many metals. Uranium not only occurs in minerals such as pitchblende (uraninite) but also, like thorium, may be enriched in various hard and resistant materials such as zircon and monazite. Weathering, wave action, and similar mechanisms may concentrate such materials into heavy mineral sands, such as the monazite sands of Brazil, southern India, and Western Australia.

261. There is a substantial worldwide industry in which materials with relatively high concentrations of uranium and thorium are mined and milled, either for the sake of the metals themselves or for the other materials that occur with them, such as the rare earths and phosphates. In addition, during the processing of some materials, concentrations of natural radionuclides, often out of secular equilibrium with their parents or daughters, may build up in scales and in other (usually waste) materials. This can happen in ore smelters, in plants that process calcium phosphate in the production of phosphoric acid and fertilizers, and in the pipes and valves on oil platforms and in refining facilities. Some of these minerals and materials are known to have the potential to cause significant occupational exposure; they are listed in Table 33 [E2, N4]. The listing is incomplete simply because the materials have not come under regulatory control and have not, as a result, been fully studied. The data in the table should therefore be regarded as illustrative rather than exhaustive. Uranium ore could have been included here but is instead considered in Chapter II, along with other sources of exposure arising in the nuclear fuel cycle.

262. The mining and milling of ores with elevated levels of natural radionuclides and their subsequent processing can lead to the exposure of personnel from external radiation and from intake, primarily inhalation [D2]. Exposure to dusts is particularly important during dry operations with bulk material in enclosed facilities. Exposures can also come from the scales that build up in the plant. During normal operations, this is likely to be largely due to external radiation; internal exposure may, however, arise during maintenance and cleaning operations. Exposure to radon needs to be taken into account, but as identified in Section V.B this route of exposure is not solely dependent on the activity concentrations of the material being handled.

263. For the purpose of determining when radiological precautions may be required in handling materials with elevated levels of natural radionuclides, some assessments of dose have been undertaken [D2, I17]. Under somewhat pessimistic assumptions, materials containing activity concentrations of between 1 and 10 kBq kg^{-1} of parent radionuclide could result in annual effective doses to workers of the order of 1 or 2 mSv from external and internal exposure. The assumptions used in the assessment of internal exposure were airborne dust concentrations of 5 mg m^{-3}, continuous occupational exposure conditions and no respiratory protection, 5 µm activity median aerodynamic diameter (AMAD), and the new ICRP dosimetry [I17]. An evaluation of the available literature has shown that handling substances containing natural radionuclides with an activity concentration of less than 1 Bq g^{-1} of the parent radionuclide generally leads to effective doses of less than 1 mSv in a year, even in the most unfavourable circumstances [S2].

264. There is a particular interest in the occupational exposures associated with mineral sands, which contain significant concentrations of thorium (up to 8%). These are mined and processed in several countries for their thorium content, although more typically for the other materials such as rare earths and rutile. Typical concentrations of thorium and uranium in commercially important minerals from Western Australia are given in Table 34. It can be seen that the industry is primarily concerned with the production of ilmenite. Monazite, however, is important because of its relatively high thorium content and its propensity to concentrate preferentially in airborne dust in the separation plant by a factor of between 10 and 30 [H4, H6, H7, J1, K1].

265. Sand mined from a suitable site undergoes a preliminary separation stage at the mine that removes approximately 90% of the light quartz minerals [J1]. The remaining heavy minerals are transported to a sand-processing plant, where further separation and concentration produces the four main commercial sand fractions: ilmenite, rutile, zircon, and monazite. Both wet and dry separation techniques are used. In Australia, measurements in one processing plant and its environs gave an average dose rate of 0.4 µSv h^{-1} [J1]. Levels close to a stockpile of monazite were reported to be up to 1.5 µSv h^{-1}. Even higher levels from monazite have been reported elsewhere: external exposure levels ranging from less than 10 µGy h^{-1} to more than 100 µGy h^{-1} in storage areas [I9, K1]. Over a working year, the exposure levels in the Australian plant were estimated to give an effective dose of 1 ± 0.5 mSv. Internal exposure has been of greatest concern, however, owing to the use of dry processing techniques and the dustiness of the operations. In the same plant, airborne dust concentrations averaged 3.3 ± 2 mg m^{-3}, with an average AMAD of 3.2 µm (GSD: 2.8); using previous ICRP dosimetry, this gives an average annual effective dose of 7 mSv [J1]. In Western Australia, around 1,500 workers are involved in the mining and processing of the heavy mineral sands and a further 500 are employed in various downstream processing activities, but only 150–200 employees are designated as radiation workers. Workers are so designated on the basis of their potential to receive an annual effective dose in excess of 5 mSv. Typically, only workers involved in the operation and maintenance of the dry separation plants would be designated as radiation workers [H4, H6, H7]. One downstream process is the practice of manufacturing gas mantles containing thorium. This is known to be widespread in many countries, however, no data were provided and no estimate has been made of the resulting occupational exposure.

266. The trends in the maximum and mean annual effective doses to designated workers over a 10-year period, 1986–1995, in the Western Australian mineral sands industry are shown in Figure XIII [H4]. Significant reductions have been achieved, the mean annual dose having declined from just under 25 mSv (90% external, 10% internal) to around 6 mSv (85% external, 15% internal) in 1990–1994. It is estimated that exposures before 1986 were higher than those shown; in plants that operated in the late 1970s and early 1980s and that produced large quantities of monazite, exposures could have been twice as high. The annual external exposures to monazite plant operators and monazite product baggers regularly exceeded 10 mSv in the 1970s [H4, H6, H7]. Most of the decline has been in the internal dose. The annual external radiation dose has remained relatively constant over the 10-year period, being in the range 1–2 mSv. In the UNSCEAR 1993 Report [U3], the average annual effective dose to 376 dry-process workers was reported to be 20 mSv for 1983–1988, with 50% of the workers above 15 mSv. About 90% of the dose for this period came from internal exposure. Further substantive reductions in airborne concentrations are considered unlikely in the absence of a fundamental change in the processing technology. The above-quoted internal exposures should be reduced by a factor of 3 to be consistent with ICRP Publication 68 [I15].

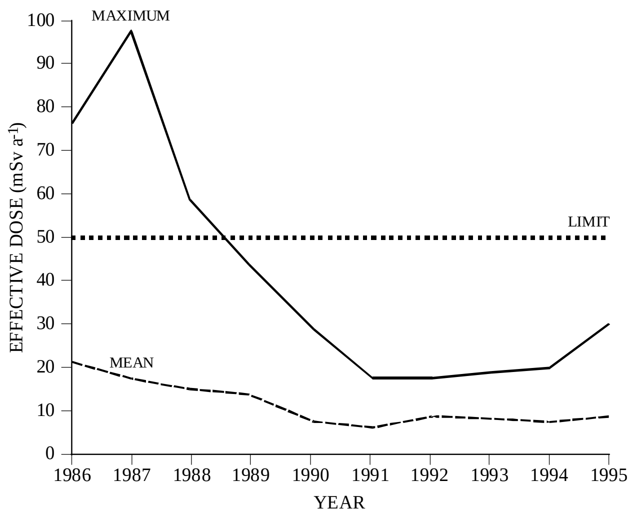

Figure XIII. Trends in effective doses to workers in the mineral sands industry in Western Austrlia [H4].

267. There have been proposals for the processing of monazite to produce rare earth metals, and a plant is likely to be built in Australia in the near future. In this plant, the monazite grain will be cracked open and the radionuclides solubilized in the process. This plant will require high standards of

occupational protection. Similarly, there have been demands for the uranium and thorium content of mineral sand products to be reduced. To do this will require chemical separation, and high standards of occupational protection will again be required [H4, H6, H7].

268. Countries other than Australia where mineral sands are mined include India, Malaysia, and South Africa. Several thousand workers in each of these countries are involved in the mining and milling of the sands. About 600 workers in China and 300 workers in the United States are involved in bastnaesite mining (a rare earth mineral also containing significant amounts of thorium) [I9]. It is also perhaps worth noting that workers in plants where the products from the processing of mineral sands are used may also receive significant exposures if precautions are not taken. For example, assessments of dose have been reported for one factory in Italy handling zircon sand for producing refractory materials [B2]. The sand had activity concentration of ^{238}U of about 3 kBq kg^{-1} and an activity concentration of ^{232}Th of about 0.8 kBq kg^{-1}. Owing to the large particle size of the material, there was effectively no inhalation hazard associated with the untreated material; the doses from external radiation were generally low, being unlikely to exceed 1 mSv in a year. However, where the material was heated and ground, annual effective doses of 5 mSv could be received (based on the old ICRP dosimetry). There was some evidence that the airborne dust was enriched in ^{210}Po.

269. Uranium and thorium are associated with phosphatic deposits of marine origin. They occur in beds of varying depths; in Florida, they occur in deposits with up to 15 m of overburden. Concentrations of ^{238}U at the surface are typically of the order of 20–40 Bq kg^{-1} and increase gradually with depth to values of the order of 700–4,000 Bq kg^{-1} immediately above or in the matrix [N4]. In mining and beneficiation, gamma radiation levels range from normal to 50–100 nGy h^{-1} over unmined land and up to 1 μGy h^{-1} near large quantities of beneficiated rock. This is not an important route of exposure, however, since annual effective doses from external radiation do not exceed 1 mSv above normal background.

270. Where the rock is handled in the dry state, there is the potential for airborne dusts, and control measures may be needed. In phosphoric acid plants, elevated gamma radiation levels have been found in some Florida facilities, with calculated values up to 0.4 mSv in a week [N4]. The greatest potential for exposure has been found to be in filter pan refurbishing, either at the plant or at off-site machine shops. External gamma radiation levels in filter pan cleaning and maintenance range from 10 μGy h^{-1} in the general vicinity to 120 μGy h^{-1} in contact with the uncleaned pan. Cumulative doses to workers would depend on a number of factors but clearly could exceed 1 mSv in a year.

271. The production processes in oil and gas extraction industries do not routinely involve the widespread dispersal of activity into the working environment, as does the handling of bulk quantities of materials. They can, however, lead to quite substantial deposits of activity in some plants. Furthermore, the physical and chemical reactions during processing can alter the state of equilibrium of the radionuclides such that individual radionuclides may become concentrated to levels many times their level in the source material. The radionuclide of principal concern for occupational exposure is ^{226}Ra (and ^{228}Ra), which accumulates in scale that must periodically be removed [H5]. The conditions and chemical composition in the well fluids and process streams vary considerably, depending on operational factors such as the characteristics and numbers of producing wells and the extent of water injection. It is also likely that the concentrations of radium-bearing compounds underground will vary between and within fields. The location and extent of scale accumulation depend on such factors as the turbulence of flow, temperature, and acidity. The consensus is that most deposition is from the aqueous phase, so the presence of water in a process stream or vessel can signal the potential for scale deposition. In oil wells in the United Kingdom, scales commonly have an activity concentration of 1–10 Bq g^{-1} but can be an order of magnitude higher [D3]. Levels as high as several kilobecquerels per gram have been reported [H5].

272. An indication of the number of workers involved in handling materials containing elevated levels of natural radionuclides is available from Germany [S2]. The number of workers involved with phosphate fertilizers who receive between 1 and 6 mSv in a year is estimated to be 1,000 in the trade (e.g. store workers) and 2,000 in the application of the material (in farming). The activity concentration of the material is above 2 Bq g^{-1} of uranium and its progeny. It was estimated that about 100 workers involved with zircon sands (activity concentration of 5–10 Bq g^{-1} of thorium decay chain radionuclides) and 30 involved with pyrrhite ore (activity concentration of natural radionuclides up to 30 Bq g^{-1}), and 10 with copper slag processing receive similar doses.

273. While a number of specific studies have been noted above, the information is fragmented and covers a wide variety of situations. It is clear that some of the operations in the mineral processing industries provide the potential for significant exposure and, as shown by the data in Figure XIII, can cause average individual doses to exceed the dose limit. These high dose situations arise largely from the potential for exposure not to be recognized and hence not to be brought under regulatory control, rather than from poor application of protection standards. This potential is driving efforts to bring such situations within a regulatory framework [E3, I5], and hopefully more coherent data will be available for future reviews. Despite the high doses noted above, the examples presented support the supposition in the UNSCEAR 1993 Report [U3] that the average annual dose to workers is unlikely to exceed 1.0 mSv. That Report made a crude estimate of some 200 man Sv from this practice, then folded in an estimate of exposure arising from coal-fired power plants of the order of 60 man Sv, and concluded that a global figure of 300 man Sv would be appropriate. Again, in the absence of firm evidence, the crude estimate of average annual collective dose worldwide of 300 man Sv is considered the best available estimate.

D. SUMMARY

274. A common feature of the estimates of exposure to natural radiation from various practices is the very limited amount of data on which the estimates are based and the high uncertainty. These estimates, summarized in Table 35, should therefore be treated with caution. The overall collective dose is very significant; some 11,700 man Sv. The main contributors are, firstly, mining (2,600 man Sv from coal mining and 2,000 man Sv from other mining) and, secondly, the above-ground (in buildings) inhalation of radon and its decay products, some 6,000 man Sv. This latter figure in particular should be regarded as a crude estimate. It is hoped that better data will be available for future assessments.

VI. DEFENCE ACTIVITIES

275. Radiation exposures to workers in defence 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. While this approach is continued here, it must be recognized that there is a degree of overlap between the categories and also that the limited number of countries responding to the UNSCEAR Survey of Occupational Radiation Exposures constrains the conclusions that can be drawn. The third broad category, that of exposure from conventional industrial, medical and research uses, has not been separately identified in the data provided and is therefore not addressed further here, but it may be a consideration for future reviews.

A. NUCLEAR WEAPONS

276. Nuclear weapons have been developed, tested, and deployed by five countries: China, France, the former USSR, the United Kingdom, and the United States. The main potential sources of occupational exposure in the development and production of nuclear weapons are the two radioactive fissile materials plutonium and uranium and tritium. Exposures may arise by 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 from gamma rays and, to a lesser extent, neutrons. Intake of these elements into the body is minimized by avoiding direct contact and providing containment for the materials during their fabrication into weapons. Some small intakes will, however, inevitably occur, and monitoring is generally undertaken to determine their magnitude. The nature and extent of monitoring depend on the potential for exposure. Where material is being processed, the monitoring may include the use of personal air samplers, whole-body monitoring, and bioassay; where the potential for intake is much less, area monitoring of airborne levels may suffice. Because of the steps taken to provide confinement for these materials, external irradiation tends to be the dominant source of exposure for those involved in the production, testing, and subsequent handling of nuclear weapons. As the energy of the gamma radiation typically emitted by the more common isotopes of these elements is relatively low, this is one area where the direct recording of the dosimeter measurement as the received whole-body or effective dose, as is common practice, could lead to significant overestimates. Neutron as well as gamma dosimeters may be used where exposures from the former may be significant.

277. In the United States, the Department of Energy (DOE) is responsible for stewardship of the nuclear weapons stockpile and the associated facilities, for restoring the environment at related sites, and for energy research [D4]. The facilities covered include accelerators, fuel/uranium enrichment, fuel fabrication, fuel processing, maintenance and support, reactor operation, research, waste management, weapons fabrication, and testing. The annual numbers of workers involved in these activities, including the number monitored and the number with measurable doses during 1990–1994, are given in Table 36. In the United Kingdom, the Atomic Weapons Establishment is the organization whose stewardship is comparable to that of the United States Department of Energy. Relevant data are given in Table 37. During the time periods covered by the four previous UNSCEAR reports, the United Kingdom and United States were the only countries that provided substantive data (these can be seen in the first part of Table 38). Included in the table are all employees, contractors, subcontractors, and visitors. Also indicated are the collective doses, in total and by component of exposure. It should be noted that between 1992 and 1993, the United States changed its method of calculating internal exposure, with the result that doses before and after these years are not directly comparable. The changes in reporting requirements had a significant impact on the collective dose over this period. The collective dose seemed to decrease by up to 28% because the dose from intakes in previous years is no longer reported in the current year.

278. In the United States the data averaged over five-year periods given in Table 38 indicate that the number of monitored workers has risen from 15,900 in 1985–1989 to 20,800 in 1990–1994. However, the most important difference is a halving of the annual collective effective dose between these two periods from 11.9 to 5.9 man Sv. A number of factors are relevant here. First, the operational status of many of the DOE facilities has changed, with many having been shut down and having gone through transition

from operation to stabilization or decommissioning. Production of plutonium at the Hanford Site ceased in 1990. In 1989, the plutonium fabrication plant at the Rocky Flats site was shut down for safety code violations, and many production functions were suspended. Plutonium operations were halted at the Rocky Flats site in 1991. By 1988, no DOE reactor was producing tritium for nuclear weapons. By 1992, the United States was no longer building nuclear weapons. This programme appears to have involved many contractors. The second relevant point is the policy on who is included in monitored workers. For 1990–1994, they included all DOE employees, contractors, subcontractors, and visitors. The Department of Energy notes [D8] that the number of monitored workers may not be indicative of the size of the exposed workforce because some establishments provided dosimetry to individuals for reasons other than radiation protection, e.g. for reasons of 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 annual dose to monitored workers thus appears to have decreased by a factor of three between the last two periods, which is somewhat more than the decrease in the average annual collective dose.

279. The number of monitored workers in the United Kingdom has stayed roughly constant, around 4,000. The average annual collective effective dose after an initial increase from 2.0 to 3.6 man Sv over the first two periods subsequently decreased by a factor of 3, to 1.2 man Sv for 1990–1994. A similar pattern is seen with the average annual dose to monitored workers, which over the four periods decreased from 0.94 to 0.28 mSv.

B. NUCLEAR-POWERED SHIPS AND THEIR SUPPORT FACILITIES

280. Nuclear-powered ships (submarines and surface vessels) are operated by several navies, in particular those of China, France, India, the former USSR, the United Kingdom, and the United States. Pressurized water-cooled reactors are the power source in almost all cases; in the former USSR several reactors are cooled by liquid metal. Radiation exposures arise on board ship and also at shore-based support facilities, where maintenance, refuelling, etc. are carried out and personnel are trained.

281. Data on occupational exposure from nuclear-powered ships and support activities in the United Kingdom for 1990–1994 are given in Table 37 on a year-by-year basis and summarized as an entry in Table 38. The data [H3, H9] stem from the Defence Radiological Protection Service (DRPS); while they cover naval activities, the data also cover components from the other armed forces and many of the industrial-style practices used by them. There may therefore be some differences between the workforces reported on for 1990–1994 and those reported on previously. However, these differences probably do not distort the data significantly. The number of monitored workers, about 6,300, was reasonably constant for the first three periods but in 1990–1994 increased to about 9,800. Despite this increase, the average annual collective effective dose dropped from 11.6 man Sv for 1985–1989 to 8.0 man Sv for 1990–1994. This continues the downward trend from 26.3 man Sv in the first period. In previous periods the total reported data were dominated by United States data, but that country did not contribute data on nuclear-powered ships for the UNSCEAR Survey of Occupational Radiation Exposures.

C. SUMMARY

282. Data on occupational exposure from all defence activities are summarized in Table 38. Although this period has seen the introduction of data from France and the Netherlands, the bulk of the data still comes from just the United Kingdom and the United States, with the latter dominating. The total number of monitored workers averaged over five-year periods has increased steadily, from about 100,000 in the first period to 140,000 in 1990–1994. The average annual collective effective dose fell from about 140 man Sv in the first period to about 80 man Sv in the second and third periods, with a significant further reduction to 33 man Sv for 1990–1994. The average annual effective dose to monitored workers decreased in each period from 1.3 mSv in the first period to 0.24 mSv for the most recent period. Given the much larger contribution made by the United States to the overall data, these parameters mainly reflect the experience in that country. Here attention is drawn to the comments made in Section VI.A, concerning nuclear weapons, and the different data coverage in the different periods.

283. The above data need qualifying with regard to their completeness, in particular to whether they include all significant occupational exposures associated with defence 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 both 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 in the context of proper 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 mining, enrichment, and fuel reprocessing attributed to the commercial nuclear fuel cycle).

284. The data presented above for all defence activities include occupational exposures for three countries that have developed and deployed nuclear weapons or that operated nuclear ships, namely, France, the United Kingdom, and the United States. Any estimate of worldwide occupational exposures from defence activities can, therefore, be made only by extrapolating the available data. Inevitably, this can only be done very approximately, and neither method of extrapolation presented in Section I.E is appropriate.

285. The UNSCEAR 1993 Report [U3] reviewed the potential for extrapolation based on 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 [U3] proposed adopting a very simple approach for estimating worldwide exposures from this source, namely, that the worldwide collective dose from defence activities is greater by a factor of 3 than the sum of that experienced in the United Kingdom and the United States. Four assumptions underlay the choice of this factor: first, the level of defence 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 with those in the United Kingdom; and, 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. Based on these assumptions, the estimated worldwide average annual collective effective dose from defence activities would have been about 400 man Sv in 1975–1979, falling to about 250 man Sv in 1985–1989, and 100 man Sv in 1990–1994. Given the coarseness of the underlying assumptions, it is not be 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 100 to 300 man Sv. This estimate is inevitably associated with much uncertainty, which can only be reduced by relevant data from China and the former Soviet Union.

VII. MISCELLANEOUS OCCUPATIONAL CATEGORIES

A. EDUCATIONAL ESTABLISHMENTS

286. 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 [U3], 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 be rightfully attributed to this category are often attributed to other broad practices of radiation, such as research in 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 an important educational role). Exposures 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.

287. The data reported by countries are given in the first part of Table 39. Worldwide levels of exposures have been estimated from national data by extrapolation within regions based on GDP. The coverage and scaling of data (by a factor of about 2.5) were similar to the coverage and scaling for industrial radiography. The collective effective dose is less well correlated with GDP than that for the other occupational categories analysed; the greater potential for non-uniform reporting of data in this category has doubtless contributed to this situation.

288. In the three previous periods the estimated worldwide number of monitored workers varied between 140,000 and 180,000, while the most recent period has seen an increase to 310,000, with the principal contributions coming from Canada, Germany, and Japan. This apparent doubling may be an overestimate attributable to the factors identified above. The average annual collective effective dose fell from 74 to 22 man Sv over the first three periods then rose to 33 man Sv for 1990–1994. Again, this might be a slight overestimate, but it is probably of the correct order of magnitude. The data show the average annual effective dose decreasing throughout all four periods, from 0.55 to 0.11 mSv. Although there is some variation from country to country, the dose profile data indicate few workers in this sector receive any significant doses. In line with this, the value for the average annual effective dose to measurably exposed workers, 1.1 mSv, is relatively small.

B. VETERINARY MEDICINE

289. 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. Poor practice may, however, 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 Survey of Occupational Radiation Exposures are given in the second part of Table 39. The countries reporting for 1990–1994 are broadly the same as in the preceding period, with one critical exception: there are no data from the United States. In 1985–1989, the United States accounted for 85,000 of the reported 96,000 monitored workers and for 36 man Sv of the 37 man Sv total for collective dose. It is therefore difficult to meaningfully compare the different periods. However, if the United States data are removed from the reported data for the previous period (1985–1989) a

comparison of sorts can be made. The number of monitored workers in each period was about 11,000. Similarly, the average annual collective effective dose was just over 1 man Sv in each period and the average annual effective doses were about 0.1 mSv in each period. There are considerable variations between and within countries over the four time periods considered. Interpretation of this data needs to take into account many of the cautionary comments made for medical diagnostic exposure, particularly in regard to the large differences that can occur depending on whether dosimeters are worn above or below any protective lead aprons.

290. The vast majority of the data for 1990–1994 comes from OECD countries. The limited data set make it difficult to interpolate and produce a world estimate. If the procedure described in Section I.E is used, a worldwide collective effective dose of 8 man Sv results. This is not considered reliable enough to give anything other than a lower bound to the possible values. The estimate for the previous period, 52 man Sv, is probably more robust, and in the absence of better data a rounded figure of 50 man Sv could be assumed.

C. OTHER OCCUPATIONAL GROUPS

291. The "other occupational groups" category was included in the UNSCEAR Survey of Occupational Radiation Exposures to ensure that no sizeable group of exposed persons was overlooked. The data provided are given in the last part of Table 39; they cover disparate groups that often cut across the other categories reported on. In total, this category covers only an average annual number of monitored workers of some 9,000, receiving an annual average collective effective dose of 9.6 man Sv and an average annual effective dose of about 1.0 mSv. It is concluded that no significant group has been missed in the UNSCEAR Survey of Occupational Radiation Exposures.

D. ACCIDENTS WITH SERIOUS EFFECTS

292. Accidents that occur in the course of work add to occupational exposures and in some cases can have serious consequences. Accidents with clinical consequences for those exposed that occurred in 1975–1994 are listed in Table 40. The incidents are separated into accidents occurring in four activities: the nuclear fuel cycle and associated research, industrial uses of radiation, tertiary education and research (including accelerators), and medical uses of radiation. Most of the data were obtained in response to the UNSCEAR Survey of Occupational Radiation Exposures. Some additional entries have been made from other compilations of accidents [I22, R5] to the extent that dose information was available or clinical consequences could be ascertained. The data are shown in graphic form in Figure XIV. There are 11 accidents listed for 1990–1994 involving 27 significantly exposed persons, 4 of whom died. The 3 fatal accidents (one each in Belarus, China and Israel) were all related to irradiation facilities; they are covered in more detail below. These fatalities are in addition to the three fatalities previously reported for irradiators (in Italy, Norway, and San Salvador [I23]). Also noted below is the death of an industrial radiographer in the United Kingdom linked to chronic high-dose exposure [L2]. With the obvious exception of Chernobyl, it is the accidents in industrial uses that dominate the data reported to UNSCEAR. Over all four periods, and excluding Chernobyl, there have been 98 reported accidents with 144 workers significantly exposed (including 8 fatalities). Some 65% of the accidents and exposed persons have been in the industrial sector, with 7 out of the 8 fatalities also being in this sector. However, it should be noted that overall (and in the categories as well) there has been a general downward trend: the number of accidents reported in the first period was 40 and the number in 1990–1994 was 11.

293. The accidental exposures listed in Table 40 are those that occurred in the course of work. This reflects the approach taken in previous UNSCEAR reports, namely to exclude two categories of accident: exposures from the theft or loss of industrial or medical sources and the accidental exposure of patients during diagnosis or therapy. The exclusion of the first of these paints a less-than-complete picture, and there are grey areas in categorizing accidents. The most obvious example is that of workers in the metals recycling industries. While these workers are not direct users, lost or abandoned sources are entering the metals recycling industry with increasing frequency [C5, D5, L6], giving rise to health and economic consequences. Indeed the problem is serious enough for the industry to be investing heavily in installed systems to check incoming scrap metal for radioactive content. It could thus be argued that occupational exposure to radiation occurs in this industry. Table 41 lists accidents that have had significant consequences and may be of relevance but do not fall within the strict definitions of occupational exposure or the time frame that is the primary focus of this Annex.

294. The Committee previously noted that because accidents were likely to have been under-reported, conclusions could not easily be drawn on trends in the number and types of accidents that were occurring. While under-reporting still exists, in recent years there has been a serious attempt by IAEA [I4, I6, I7, I8] to study the detailed causes of some of the more serious accidents with a view to learning lessons that might be applied to future operations of a similar nature. There has been much interest in industrial irradiators, in which a number of fatal accidents have occurred. Such accidents inevitably arouse considerable interest, and it is likely that the information now available is reasonably complete. The degree of under-reporting of non-fatal accidents with clinical consequences is, however, still unclear. The information on the accidents in irradiator facilities given here comes largely from published reports, particularly a recent IAEA review of the lessons from industrial irradiator accidents [I8]. Industrial radiography is another area where accidents with clinical effects continue to occur. Once again, most of the information comes from published reports [L3, L4], but undoubtedly it is far from complete.

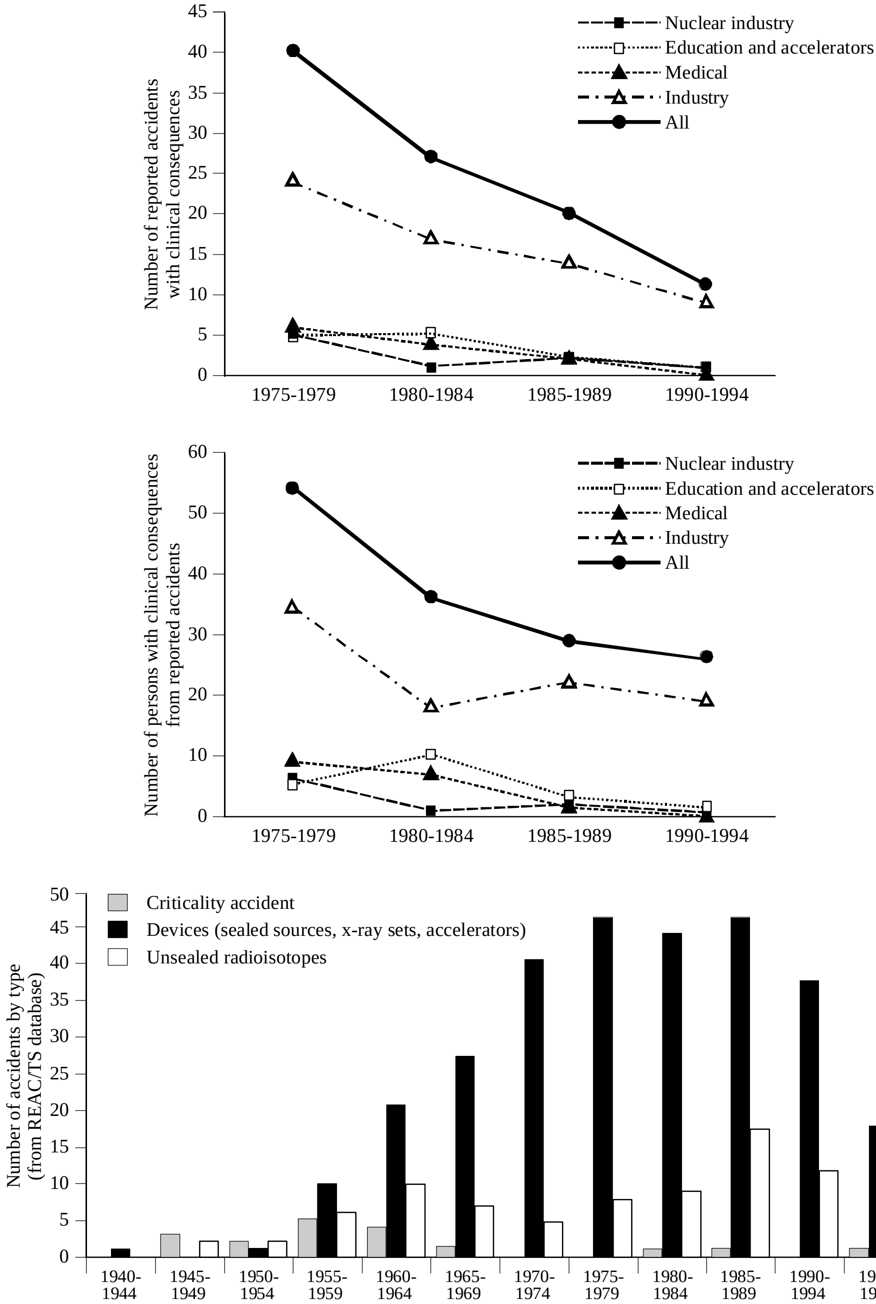

Figure XIV. Trends in accidents with clinical consequences.

295. ***Irradiators.*** Use of industrial gamma and electron beam irradiators for a range of industrial purposes began in the late 1950s in industrialized countries and later spread to other countries. There are now more than 160 gamma irradiation facilities and over 600 electron-beam facilities in operation worldwide [I8]. During the early years of the industry (until 1975), no fatal accidents occurred, but since 1989, a number of serious accidents have been reported [I4, I6, I23]. Between 1975 and 1994, six fatal accidents were reported. The first was in Italy in 1975, the second in Norway in 1982, and the third in El Salvador in 1989 [I23]. All of these were listed in the UNSCEAR 1993 Report [U3]. The three additional fatal accidents occurred during the period being covered here: the first and second in China and Israel in June 1990 and the third in Belarus in October 1991. There were also several serious non-fatal irradiator accidents during the period under review.

296. The fatal accident in China involved an irradiation facility (0.85 PBq ^{60}Co) used for sterilizing traditional Chinese medicines. One of the two doors in the entry route had been out of commission for some time due to a motor failure, and because of a power failure the interlock on the second door was not operable. Seven workers entered to re-arrange the product boxes but could not see the position of the source due to a metal shroud. Two of the workers received doses of 11 and 12 Gy and subsequently died. The fatal accident in Israel involved an irradiator facility (12.6 PBq ^{60}Co) used for sterilizing medical products and spices for the food industry. A distorted carton containing materials to be

irradiated became jammed on the conveyor transport system while the source was in the exposed position. The operator disregarded the warning signal from a gamma monitor, used an improper entry procedure to defeat the safety system, and entered the irradiation room. His whole-body dose was estimated to be about 10–15 Gy. Despite intensive medical care, he died of radiation effects 36 days after exposure [I4]. In the fatal accident in Belarus, an operator was exposed to radiation in an industrial irradiator, again following a jam in the product transport system, with the source (30 PBq ^{60}Co) in the exposed position. At the time of the accident, the irradiator was being used to sterilize medical equipment. The precise details of the actions of the operator are not known, although it is clear that the specified operating procedures were not followed and the safety features were circumvented. After reconstruction of the accident, a mean whole-body dose of approximately 11 Gy, with localized areas of up to 18 Gy, was estimated. Despite intensive medical treatment, the operator died 113 days after exposure [I6].

297. Three workers received significant doses from a linear accelerator of the van de Graaff type in France in July and August 1991. Reported doses ranged up to 40 Gy to the skin for the most irradiated of the three [C1, Z1]. According to the published reports, the accident was due to negligence and non-compliance with regulatory requirements. The accelerator was used to treat a granulated form of polytetrafluoroethylene. All three workers entered the facility through the exit of the conveyor. Their exposure was a result of the dark current associated with the accelerator after it had been switched off but with the accelerator voltage maintained to save time. The residual dose rate was a few grays per second. One suffered severe skin lesions; the other two were less seriously affected. An accelerator operator was overexposed at an industrial irradiation facility in Maryland in the United States in December 1991 [I8, S1]. The radiation source was a 3-MV accelerator for producing high electron beam currents for the processing of materials, typically polytetrafluoroethylene powder, wire, and plastic pellets. During maintenance, the operator placed his hands, head, and feet in the beam. This was done with the filament voltage of the electron source turned off but with the full accelerating potential on the high-voltage terminal. The operator was therefore exposed to the electron dark current, which was sufficient to produce dose rates of the order of 0.4–13 Gy s^{-1}. Three months after the accident, the four digits of the operator's right hand and most of the digits of his left hand had to be amputated; he also suffered hair thinning on the scalp after two weeks. A mean estimated dose to the man's fingers obtained by electron paramagnetic resonance spectrometry was of the order of 55 Gy. Also in November 1992, four workers were over-exposed in an irradiation facility in China [P1, S4]. The details obtained so far are sparse. The situation was described as involving a power loss and out-of-order safety interlocks. One of the workers suffered acute radiation syndrome.

298. ***Research accelerator.*** In November 1992, an individual entered an electron accelerator research facility in Hanoi, Viet Nam, without the operator's knowledge and unwittingly exposed his hands to the x-ray beam [I7]. He was adjusting a sample to be irradiated when, owing to the lack of safety systems and procedures to prevent it, the operator switched on the machine. Exposure was only a few seconds but at a very high dose rate, and the severity of radiation damage led within months to amputation of the whole of one hand and the fingers of the other. On the basis of a physical dosimetry calculation using all the information available, a most probable dose of 10–25 Gy was estimated for the left hand and 20–50 Gy for the right one.

299. ***Industrial radiography.*** An industrial radiographer in the United Kingdom died in 1992, probably as a result of substantial radiation exposure received over several years [L2]. His total average whole-body dose was estimated to be at least 10 Gy; a much larger dose to a hand required partial amputation of the hand. The cause of his death was acute myeloid leukaemia. The exact circumstances of his exposure were not established. He had, however, been working in industrial radiography since 1974. Until 1983, he worked with torch-type containers using ^{192}Ir sources. Thereafter he worked with wind-out, remotely operated ^{192}Ir sources. Doses recorded by his individual monitors were unremarkable, his lifetime recorded dose being 104 mSv.

300. Outside the period of direct interest there were other accidents involving industrial radiography. In France in 1995, an accident occurred during the handling of a 1 TBq ^{192}Ir gamma radiography source by an employee of a boiler-making firm [K2]. Although the employee's hands showed clinical effects, these were ignored until routine processing of the employee's dosimeter revealed a dose equivalent of 200 mSv. The circumstances of this accident have not yet been determined. The clinical development of the lesions and a thermographic analysis both indicated that the local dose had exceeded 30 Gy. In Iran in 1996, as a result of poor procedures in a confined situation, a worker received an estimated 3 Gy to the whole body and up to 50 Gy to the chest [O10] in connection with the use of an ^{192}Ir source. In 1999, in Peru, a welder picked up an ^{192}Ir source and put it in his pocket. He received approximately 3 Gy whole body but up to 100 Gy to a buttock [O10].

301. ***Criticality.*** In 1997, a worker at the nuclear weapons research centre of Arzamas-16 in the Nizhny Novgorod region of the Russian Federation received a whole-body gamma-neutron dose of 14 Gy with 200 Gy to the hands as a result of a criticality accident with a weapons-grade ^{235}U assembly. The worker died three days after the accident while undergoing treatment in a Moscow hospital [O10]. In 1999 at Tokai Mura, Japan a criticality accident occurred in a fuel conversion plant, involving the processing of highly enriched fuel for an experimental fast reactor. Using unauthorized procedures, the workers poured 16.6 kg of 18.8% enriched uranium into a precipitation tank, resulting in the critical excursion. The three workers involved received doses of approximately 17, 8, and 3 Gy; the two workers receiving the highest doses later died, the first 83 days and the second 211 days after the accident [I25, S8].

302. ***Loss of control of sources.*** In Xinzhou, China in 1992, a farmer who was working on a site demolishing a former irradiation facility picked up a cylindrical steel bar and put it in his pocket. He became ill the same day, and the bar went with him to the hospital. The bar contained a 0.4 TBq ^{60}Co source. The farmer, his brother and father all received doses in excess of 8 Gy and died; 14 other persons received doses in excess of 0.25 Gy. In Tammiku, Estonia, in 1994, a ^{137}Cs source (a few terabecquerels) thought to have been part of an irradiator was disposed of as scrap metal [I24]. It was recovered and stored in a source store with limited security. The store was broken into and the source removed. Six people, exposed to varying degrees up to 4 Gy whole body, developed a variety of lesions. One localized exposure was up to 1,800 Gy and the person died. Eleven frontier guards were exposed to one or more sources of ^{137}Cs with activities up to 150 GBq at the Lilo Training Centre near Tbilisi, Georgia [G3]. The sources had belonged to a former administration. The incident occurred over a period spanning 1996 and 1997. The sources were intended for training civil defence specialists or for calibration. Some of the sources had been removed from their containers, either still fixed in the source holder or separate from it. Information on the irradiation is incomplete, but it appears that at least one source was kept in the pocket of a coat. Each of the guards suffered from one or more acute localized irradiation lesions of varying seriousness; several suffered from nausea and vomiting. In Istanbul, Turkey, in 1998, a 3 TBq ^{60}Co therapy source inside a shielded transport container was sold as scrap. The individuals who purchased the source were unaware of the radiation hazard and proceeded to break open and dismantle the container in a residential area of Istanbul. Those involved started to suffer from the acute radiation syndrome, and further work was stopped. The cause of these symptoms was not recognized for some weeks. A total of 18 persons, including 7 children, were admitted to hospital. Five exhibited clinical effects of acute radiation exposure, with one person having signs of radiation-induced skin injuries on the fingers of one hand. The 3 TBq ^{60}Co source was recovered. It was initially thought that a second ^{60}Co source had also been dismantled in this accident, but that appears now not to have been the case [O10]. In Bangkok, Thailand in February 2000, poor source security resulted in three old radiotherapy heads being taken to a scrap yard. One source, estimated to be about 15.5 TBq ^{60}Co, was removed from its shielding. The resulting exposure caused 10 persons to be hospitalized, and three of these subsequently died.

303. While accidents causing death are relatively well known, there is likely to be a substantial under-reporting of other accidents, and even where information is available it is often fragmented. The UNSCEAR 1993 Report [U3] noted that a study [R6] of published material dealt with only about half the accidents covered in UNSCEAR reports. Recognizing that the lessons learned from accidents are important for preventing future accidents, a number of countries and international organizations have been setting up accident data-bases that should help future reporting. Examples are the IAEA's Radiation Event database (RADEV) [O10]; in the United Kingdom, the Ionizing Radiations Incident Database (IRID) [C6, T2]; and in the United States the Registry kept by REAC/TS [C7]. Caution needs to be exercised when comparing databases because of differences in scope, time frames, and categories. The REAC/TS database, which is summarized in Table 42 and Figure XIV, covers 1944 to 1999 and accidents involving the public and patients. Despite these differences and the inevitable bias towards data from the United States, which accounts for some two thirds of the data, the information paints an overall picture. Three quarters of the accidents occurred in the industrial sector, which is consistent with the UNSCEAR data. It also shows a downward trend in recent times, but unlike the UNSCEAR data, this does not start to be apparent until the beginning of the 1990s.

E. SUMMARY

304. Excluding the Chernobyl accident, the 98 occupational accidents reported to UNSCEAR for 1975–1994 covered 144 workers and included 8 fatalities. Owing to under-reporting, the actual number of accidents may have been two or three times greater, and there have been significant accidents connected with occupational uses of radiation but that exposed persons not directly employed in the original practice. Although the available data seem to suggest a downward trend, this should be treated with caution. Papers presented at a joint IAEA, European Community, Interpol, and the conference of the World Customs Organization (WCO) in 1998 on the safety of radiation sources and security of radioactive materials [C6, D5, L6] suggest that more accidents are coming to light.

CONCLUSIONS

305. Occupational radiation exposures have been evaluated for six broad categories of work: the nuclear fuel cycle, medical uses of radiation, industrial uses, defence activities, education and veterinary uses, and occupations where enhanced exposures to natural sources of radiation may occur. Results for 1990–1994 are summarized in Table 43 and, in abbreviated form, for the whole period of interest (1975–1994) in Table 44. The contribution of each category to overall levels of exposure and the trends with time are illustrated in Figure XV. The worldwide average individual and collective effective doses have been derived largely from data reported to the UNSCEAR Survey of Occupational Radiation Exposures, supplemented, where appropriate, by data from the literature.

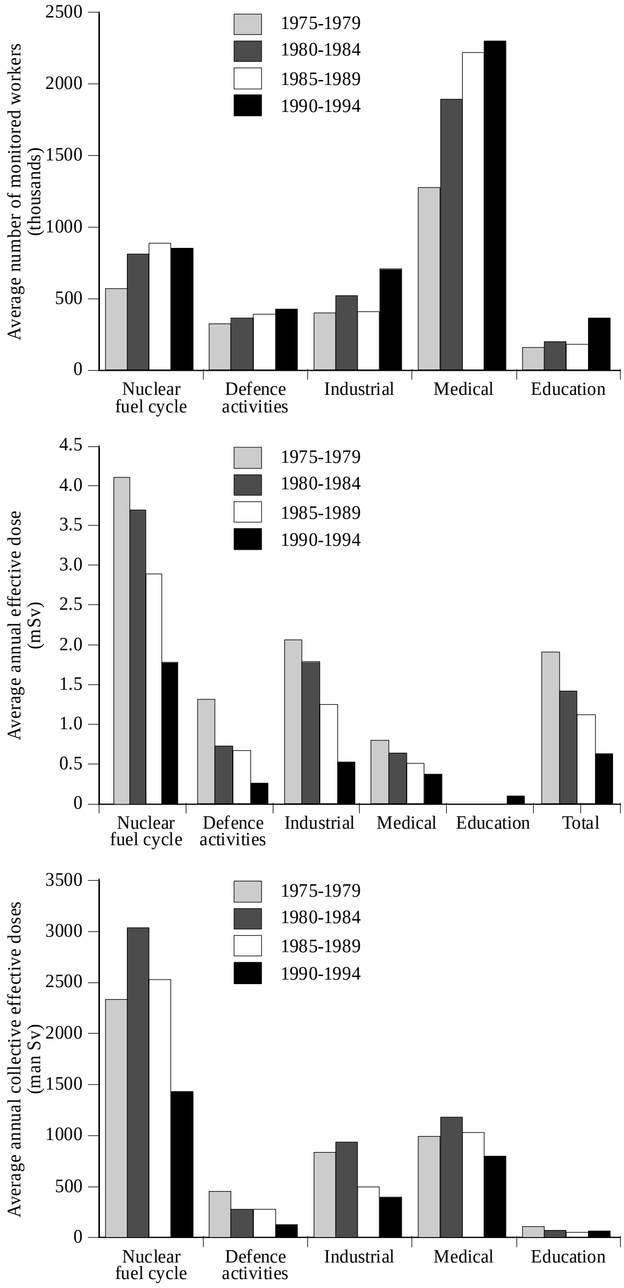

Figure XV. Trends in worldwide average annual number of monitored workers, doses to workers, and collective effective doses from man-made sources of radiation.

306. The worldwide average annual collective effective dose to workers from man-made sources of radiation in the period 1990–1994 is estimated to be about 2,700 man Sv. The collective effective dose from exposures to natural sources (in excess of average levels of natural background) is estimated to be about 11,700 man Sv. The largest component of this, 6,000 man Sv, comes from a category new to UNSCEAR reviews, namely, the exposure of workers to radon and its progeny significantly above background levels. Of the remainder, the largest components are 2,600 man Sv for coal mining and 2,000 man Sv for other mining operations (excluding uranium mining, which is dealt with in the nuclear fuel cycle). There are contributions of 800 man Sv to aircrew from exposure to cosmic radiation and 300 man Sv to those involved in the minerals processing industries. The estimated collective dose from natural sources of radiation is, however, associated with much greater uncertainty than that from man-made sources of radiation.

307. Of the annual collective effective dose from exposure to man-made sources of radiation (2,700 man Sv), about 50% arises from operations in the nuclear fuel cycle (1,400 man Sv), about 30% from medical uses (760 man Sv), about 14% from industrial uses of radiation (360 man Sv), about 4% from defence activities (100 man Sv), and about 2% from educational and veterinary activities (40 man Sv). The contribution from medical uses of radiation may, however, be an overestimate by a factor of 2 or more; most of the exposures from this source arise from low-energy x rays from diagnostic radiography, and the dosimeter readings, which are generally entered directly into dose records, may overestimate the effective dose by a large factor.

308. The average annual effective dose to monitored workers varies widely from occupation to occupation and also from country to country for the same occupation. The worldwide average annual effective doses to monitored workers in industry (excluding the nuclear fuel cycle), medicine, educational and veterinary activities are less than 1 mSv (about 0.51 mSv, 0.33 mSv, and 0.11 mSv, respectively). In particular countries, however, the average annual dose for some of these occupations is several millisievert or even, exceptionally, in excess of 10 mSv. The average annual effective doses to workers in the nuclear fuel cycle are, in most cases, larger than the doses to those in other occupations; for the fuel cycle overall, the average annual effective dose is about 1.75 mSv. For the mining of uranium, the average annual effective dose to monitored workers in countries reporting data was about 4.5 mSv, and for uranium milling operations, it was about 3.3 mSv. There are, however, very wide variations about these average values, with doses of about 50 mSv being reported in some countries. The average annual effective dose to monitored workers in LWRs is about 1.4 mSv, with doses about 20% greater, on average, in HWRs (1.7 mSv) and smaller by a factor of about 3, on average, in GCRs (0.5 mSv). Directly comparable data were not available for LWGRs, but other data suggest doses could be 10–15 mSv. The individual doses in fuel reprocessing are about 1.5 mSv, whereas those in fuel enrichment are much smaller, <0.1 mSv.

309. The percentage of monitored workers worldwide who worked with man-made sources of radiation and who received annual effective doses in excess of 15 mSv is estimated, on average, to have been less than 1% during the period 1990–1994. There is, however, considerable variation in this value by occupation. Typically, fewer than 0.1% of monitored workers in medicine and industry (excluding the nuclear fuel cycle and defence) are estimated to have received doses in excess of this level. For the nuclear fuel cycle as a whole, about 1% of monitored workers, on average, exceeded this level of annual effective dose. However, there is considerable variation between different stages of the fuel cycle (e.g. about 10% for uranium mining).

310. The percentage of the worldwide collective effective dose from all uses of man-made sources of radiation (or, more strictly, for those uses for which data have been reported) that arises from annual individual doses in excess of 15 mSv is estimated to have been about 13% during 1990–1994. There is, however, considerable variation in this value from one occupation to another. Typically, about 14% and 25%, respectively, of the collective dose in medicine and industry (excluding the nuclear fuel cycle and defence) is estimated to have arisen from annual individual doses in excess of this level. For the nuclear fuel cycle as a whole, about 11% of the collective dose arose from annual individual doses in excess of 15 mSv. There is, however, considerable variation between different stages of the fuel cycle: about 32% for uranium mining and milling, about 8% averaged over all but LWGR reactors, about 13% for fuel reprocessing, about 11% for fuel fabrication, and essentially zero for enrichment. In this Annex for the first time some data have been available on the percentages of workers exceeding other dose values, namely 10 mSv (NR_{10}), 5 mSv (NR_5), and 1 mSv (NR_1), and on the percentage of the collective dose coming from individual exposures exceeding these values, SR_{10}, $SR_{5,}$ and SR_1. The data are not sufficiently robust to produce worldwide values, but for some of the practices they provide a better insight into the dose profiles underlying the limited indicators NR_{15} and SR_{15}. With the ongoing decreases in collective and individual doses, these additional parameters, i.e. NR_{10}, NR_5, NR_1 and SR_{10}, SR_5, SR_1, will become more important.

311. For the 1990–1994 period, significantly more data than in previous periods were available on average annual effective doses to measurably exposed workers. This has allowed for the first time reasonably robust worldwide estimates to be made for many of the practices. For the nuclear fuel cycle, the value was 3.1 mSv, higher by a factor of about 2 than the value for monitored workers (1.75 mSv). In each of the remaining categories for which an estimate was available the measurably exposed values were higher by a factor of about 4 than those for monitored workers: 1.4, 2.2, and 1.0 for medical uses, industrial uses, and educational/veterinarial uses, respectively. Considerable variation about these general factors is seen when individual practices are examined. For example, in uranium mining there is little difference between the average annual effective dose to workers of 4.5 mSv and the corresponding value of 5.0 mSv for measurably exposed workers, while in dentistry there is more than tenfold difference between the values of 0.06 mSv and 0.89 mSv for monitored workers and measurably exposed workers, respectively. When viewed together with the NR and SR parameters for each practice, these data provide a clearer picture of the dose profiles than was previously available.

312. The average annual effective dose to workers exposed to enhanced levels of radiation from natural sources, in particular in underground mines, varies considerably between mines and between countries. In coal mines, the average annual effective dose is estimated to be about 0.7 mSv. In other (non-uranium) mines, the worldwide average effective dose is estimated to about 2.7 mSv. Aircrew are estimated to receive an average annual effective dose of about 3 mSv.

313. ***Trends in exposures over the period 1975–1994.*** Trends in exposure from man-made sources are illustrated in Figure XVI for each of the main occupational categories considered in this Annex. No attempt has been made to discern any trends in occupational exposures from natural sources, because insufficient data are available to make meaningful estimates; the few data that do exist, however, suggest that exposures in mining operations and minerals processing in earlier periods were greater than those estimated here, possibly much greater. This is so because somewhat less attention was given in the past to the control and reduction of exposures in underground mining.

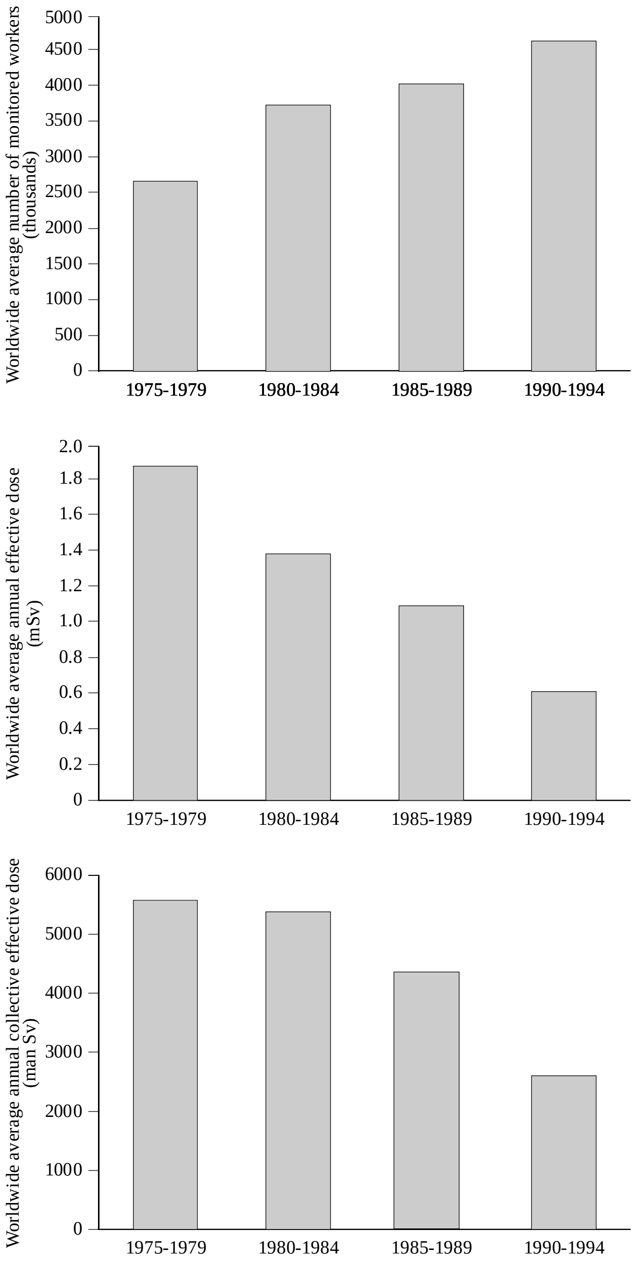

Figure XVI. Overall trends in worldwide occupational exposures to man-made sources of radiation.

314. The worldwide annual average number of workers involved with man-made uses of radiation is estimated to have increased from about 2.7 to about 4.6 million between the first and fourth five-year periods. The greatest increase (from about

1.3 to about 2.3 million) was in the number of monitored workers in medicine. The number of monitored workers in the nuclear fuel cycle also increased significantly, by about 50%, from about 0.6 million in the first period to about 0.9 million in the third period, but for 1990–1994 it dropped to 0.8 million. In defence activities and industrial uses there have been some variations, but overall both increased by about 30%, with defence activities rising from about 0.3 to 0.4 million and industrial uses rising from about 0.4 to 0.7 million workers.

315. The annual collective effective dose averaged over five-year periods for all operations in the nuclear fuel cycle varied little about the average value of 2,600 man Sv between 1975 and 1989 despite a three- to fourfold increase in electrical energy generated by nuclear means. The latter has continued to increase, but the average annual collective effective dose has fallen by a factor of about 2, to 1,400 man Sv. A significant part of this reduction 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. This estimated reduction is based on limited data, so its magnitude 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, and a more general move to open-pit mining, support the view that a substantial reduction has taken place. In other parts of the nuclear fuel cycle the situation is more varied, for example, in reprocessing the downward trend in previous values, 53, 47, and 36 man Sv, has been reversed with an increase to 69 man Sv for 1990–1994, although to a large degree this simply reflects the inclusion of Russian data for the first time. However within the nuclear fuel cycle the other important element, other than mining, is reactor operation, which after increasing from 600 to 1,100 man Sv over the first three periods dropped to 900 man Sv for 1990–1994.

316. The normalized collective effective dose per unit energy generated has decreased with time for the fuel cycle overall and for most of its stages. For the fuel cycle overall, it has decreased by a factor of about 3, from about 20 man Sv $(GW\ a)^{-1}$ to about 9.8 man Sv $(GW\ a)^{-1}$, with most of the decrease occurring during the last two periods. For reactors between the first and second five-year periods, the normalized collective doses changed little, but large decreases occurred in the next two periods (first by a factor of 1.7 and then by a factor of 1.5). The UNSCEAR 1993 Report [U3] linked the first of these reductions to completion of most of the safety modifications following the accident at the Three-Mile Island reactor and to much greater attention paid by utilities and regulators to reducing occupational exposure in both existing and new reactors. This latter downward pressure on doses continued into the 1990–1994 period and indeed was given new impetus by changes in risk factors and consequent recommendations from ICRP [I12] for reductions in the dose limits. The above trends are also reflected in the average annual effective dose to monitored workers, which in the nuclear fuel cycle has been consistently reduced over the whole period, from 4.1 mSv to 1.75 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 value for the fourth period was reported, other indicators suggest at least that the high level of exposure was maintained.

317. The worldwide average annual collective effective dose from all industrial uses of radiation (excluding the nuclear fuel cycle and defence activities) was fairly uniform over the period 1975–1984, at between 800 and 900 man Sv. It decreased, however, by a factor of almost 2 in the second half of the 1980s (to 490 man Sv) and then fell further, to about 360 man Sv, in 1990–1994. The same trend is reflected in estimates of individual dose: the average annual effective dose to monitored workers decreased from some 2.1 mSv in 1975–1979, through 1.8 mSv and 1.2 mSv, to 0.51 mSv in 1990–1994. It should be noted that in previous UNSCEAR reports industrial uses included a component from educational uses, which tended to distort the data. In this Annex, educational uses are dealt with in a separate category, and the industrial data for earlier years have been adjusted to remove the educational component. In defence activities, both the average individual and collective doses fell by a factor of about 4 over the whole period, from 1.3 mSv to 0.24 mSv and from 420 man Sv to 100 man Sv, respectively.

318. The worldwide average annual collective effective dose from all medical uses of radiation, about 1,000 man Sv, changed little over the first three five-year periods but then dropped significantly, to 760 man Sv, in 1990–1994. A clear downward trend is evident in the worldwide average effective dose to monitored workers, which decreased from about 0.78 mSv in the first five-year period to about 0.33 mSv in the fourth; there was, however, considerable variation between countries. The annual average number of monitored workers in medicine increased steadily over the four periods, almost doubling, from 1.3 million to 2.3 million. It is for this reason that the collective dose remained relatively uniform with time, notwithstanding the significant decrease in average individual dose. The extent to which some of these decreases in average individual dose are real or are merely artifacts due to changes in monitoring or recording practice warrants further analysis.

319. The percentage of monitored workers worldwide involved with all uses of man-made sources of radiation who received annual effective doses in excess of 15 mSv has decreased progressively, from an average of about 5% in the first period to 3% in the third period, and to less than 1% for 1990–1994. This same downward trend is evident in the percentages of nuclear fuel cycle and medical workers worldwide receiving annual doses in excess of that same level. The tabulated data for medical workers show an increase in the third period. The increase is more apparent than real, however, and is due to the inclusion for that period of data from a country that had previously not reported data, and which significantly increased the worldwide estimate. If that country were excluded, the trend would be downwards for medical workers throughout the period [U3]. For industrial workers worldwide (excluding the nuclear fuel cycle and defence), the trend is less consistent but overall has been downward.

320. The percentage of the worldwide annual collective effective dose from all man-made uses of radiation arising from annual individual doses in excess of 15 mSv also decreased progressively, from about 45% to about 36%, on average, between the first and third five-year periods. This decrease was greater between the third and fourth periods, with a value for 1990–1994 of 13%. The same downward trend is evident for the collective dose from the nuclear fuel cycle and from medical uses of radiation. The tabulated data for medical uses show an increase in the third period; however, for the reasons set out above, this increase is merely an artifact of the data, and the trend has in fact been downwards over the whole period. For industrial workers, there is little evidence of any clear trend with time in the fraction of the collective dose arising from annual doses in excess of 15 mSv, although over the whole period it has fell from 35% to 25%.

321. Occupational exposures to workers caused by accidents give an added component of dose or injury to those involved. The data compiled indicate that most of the accidents occurred in the industrial use of radiation and that most of them involved industrial radiography sources. The great majority of accidental exposures of sufficient magnitude to cause clinical effects were associated with localized exposures to the skin or hands. From 1975 to 1994, 36 people died as a result of radiation exposures received in accidents; 28 of these deaths were at Chernobyl. A significant feature of the more recent accidents is the three fatal accidents in industrial irradiation facilities: in El Salvador, 1989 [I23]; in Israel, 1990 [I4]; and in Belarus, 1991 [I6]. From 1975 to 1994, about 98 accidents to workers worldwide with actual clinical consequences were reported. Because non-fatal accidents may be under-reported, the actual number may have been somewhat greater.

322. 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 Survey of Occupational Radiation Exposures and have led to improved estimates of occupational exposures.

323. The Committee’s current estimate of the worldwide collective effective dose from man-made sources for the early 1990s, 2,700 man Sv, is lower by a factor of about 2 than that made by the Committee for the late 1970s. A significant part of the reduction comes in the nuclear power fuel cycle, particularly in uranium mining. However, reductions are seen in all the main categories: industrial uses, medical uses, defence activities, and education. This trend is also reflected in the worldwide average annual effective dose, which has fallen from about 1.9 mSv to 0.6 mSv.

324. No attempt has been made to deduce any trend in the estimates of dose from occupational exposure to natural sources of radiation, as the supporting data are somewhat limited. The UNSCEAR 1988 Report [U4] made a crude estimate of about 20,000 man Sv from this source, which was subsequently revised downward to 8,600 man Sv in the UNSCEAR 1993 Report [U3]. The comparable figure for 1990–1994 is 5,700 man Sv; however an important new element has been added for this period, namely occupational exposure to elevated levels of radon and its progeny, bringing the overall estimate to 11,700 man Sv. This is still considered to be a crude estimate and much better data are required. This will be a challenge for the next assessment by the Committee of occupational radiation exposures.

Table 1
Occupational categories used by UNSCEAR for evaluating exposure

Exposure source	*Occupational categories*
Nuclear fuel cycle	Uranium mining Uranium milling Uranium enrichment and conversion Fuel fabrication Reactor operation Fuel reprocessing Research in the nuclear fuel cycle
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
Natural sources	Civilian aviation Coal mining Other mineral mining Oil and natural gas industries Handling of minerals and ores
Defence activities	Nuclear ships and support activities All other defence activities
Miscellaneous	Educational establishments Veterinary medicine Other specified occupational groups

Table 2
Dose monitoring and recording procedures for occupational exposure
Data from UNSCEAR Survey of Occupational Exposures

Country / area	*Occupation*	*Minimum detectable level (MDL) or recording level (mSv)*	*Dose recorded when less than MDL (mSv)*	*Dose recorded for lost dosimeters*
Argentina	All	0.1	0.00	
Australia [a]	All	0.01 x ray 0.07 gamma ray	0.00	
Brazil [a b]	All	0.2	0.00	Average value
Bulgaria	Reactor operation Nuclear medicine and radiotherapy All other medical uses Industrial radiography – x-ray All other	1.00 2.00 0.40 0.40 2.00	0.33 1.00 0.20 0.20 1.00	
Canada	All	0.20	0.00	
China		0.03	0.015	
China, Taiwan Province [b]	Reactor operation (PWR) Reactor operation (BWR) All other	0.05 0.08 0.08	0.00 0.00 0.00	Average of colleagues' doses for same period
Croatia	All	0.05	0.00	
Cuba	All	0.20	0.20	
Cyprus	All	0.20	0.05 (1990) 0.00 (1991–1994)	
Czech Republic [b]	Reactor operation Research in the nuclear fuel cycle All other	0.10 1.20 0.05	0.00 0.00	
Denmark [b c]	Research in the nuclear fuel cycle All other	0.20 0.10	0.00 0.00	0.00 0.00
Ecuador	All	0.20 or 0.10 (different laboratories)		
Finland [b]	Reactor operation Other	0.10 0.30	0.00 0.00	
France	Nuclear fuel cycle	1990-1993 0.15 COGEMA 0.10 EDF 0.35 CEA 1994 0.20 All	 0.00	
Gabon	Uranium mining and milling All other	0.99 0.01	calculated 0.01	
Germany	Mining (other than uranium) All other	0.001 0.10	0.00 0.00	Attributed by controlling authority
Greece [c]	All	0.20	0.00	
Hungary	Reactor operation All other	0.10 0.35	0.00 0.00	
Iceland	Well logging Medical uses	0.20 0.05	0.00 0.00	
India	All	0.05	0.00	
Indonesia	Reactor operation Radioiosotope production Well loggers Educational establishments	0.05	0.05	
	All other industry	0.01	0.01	

Table 2 (continued)

Country / area	*Occupation*	*Minimum detectable level (MDL) or recording level (mSv)*	*Dose recorded when less than MDL (mSv)*	*Dose recorded for lost dosimeters*
Ireland	All	0.15 Film 0.10 TLD		
Japan	All	0.10	0.00	
Jordan	Radiotherapy	0.4	0	
Kuwait		0.2	0.1	
Mexico	All	0.25	0.00	5.00
Myanmar	All	0.01		
Netherlands	All	0.01		
Pakistan	All	0.10		
Peru	All	0.10	0.00	
Poland	All industrial uses	0.50	0.25	
Slovakia	All	0.10	0.00	
Slovenia	Nuclear fuel cycle Diagnostic and dental radiology Nuclear medicine Radiotherapy Industrial radiography All other industrial uses	0.01 0.04 0.1 0.005 0.1 0.1	 0.00 0.10 0.00 0.10 0.00	
South Africa	All	0.20	0.00	
Sri Lanka	All	0.05		
Sweden	All	0.1	0.00	
Switzerland	All	0.01	0.00	
Syria	All	0.20	0.10	
Syrian Arab Rep.	All those using devices	0.2	0.00	Mean value for last 12 months
Tanzania	All	0.10		
Thailand	Reactor operation Radioisotope production Nuclear medicine and radiotherapy All other	0.2 0.2 0.15 0.02	0.00 0.00 0.00 0.00	
United Kingdom	All	0.1	0.00	

a All data refer to external exposure.
b Doses to contractors included.
c Corrections made to avoid double entries.

Table 3
Exposures to workers from uranium mining [a b]
Data from UNSCEAR Survey of Occupational Exposures

Country / area and period	Annual [c] amount of ore extracted (kt U)	Equivalent amount of energy (GW a)	Monitored workers [d] (thousands)	Measurably exposed workers (thousands)	Annual collective effective dose: Total [d] (man Sv)	Annual collective effective dose: Average per unit uranium extracted (man Sv per kt)	Annual collective effective dose: Average per unit energy generated (man Sv per GW a)	Average annual effective dose (mSv): Monitored workers	Average annual effective dose (mSv): Measurably exposed workers	Distribution ratio (number of workers): NR_{15}	NR_{10}	NR_5	NR_1	Distribution ratio (collective dose): SR_{15}	SR_{10}	SR_5	SR_1
Argentina [e]														0.95			
1975–1979	0.108	0.492	0.37		4.89	45.3	9.9	13.2		0.54							
1980–1984	0.146	0.664	0.95		2.29	15.7	3.4	2.41									
1985–1989	0.465	2.77	0.51		1.25	2.7	0.59	2.45		0.00				0.00			
1990–1994	0.071	0.423	0.21	0.13	0.36	5.07	0.85	1.70	2.73	0.00	0.00	0.00	0.62	0.00	0.00	0.00	1.00
Australia																	
1985–1989	(3.60)		0.46	0.46	1.88	(0.52)		4.11	4.11	0.05				0.19			
1991–1994	(2.82)		0.28	0.26	0.37	0.13		1.33	1.43	0.00	0.00	0.01	0.51	0.00	0.01	0.04	0.86
Canada [f g h]																	
1975–1979	6.82	31.0	6.22	5.47	41.2	6.04	1.33	6.62	7.53	0.20				0.57			
1980–1984	8.22	37.5	8.88	7.42	50.6	6.16	1.35	5.70	6.82	0.23				0.62			
1985–1989	11.81	53.5	6.28	5.24	31.6	2.68	0.59	4.80	6.04	0.21				0.67			
1990-1994 [e]	9.00	40.90	2.43	1.94	8.69	0.97	0.21	3.58	4.46	0.04	0.11	0.26	0.58	0.18	0.44	0.75	0.96
China																	
1985–1989	(0.80)		6.6		114			17.3									
1990–1994	(0.76)		[2.1]		[48]												
Czech Rep. [i j]							7.45										
1975–1979	1.78	8.11	9.06		60.4	33.9	5.47	6.67									
1980–1984	2.02	9.19	8.48		50.2	24.8		5.92									
1985–1989	1.96	8.93	7.46		36.9	18.8	4.14	4.95		0.12				0.28			
1990–1994	0.60	2.72	1.36	1.03	20.6	34.5	7.59	15.2	15.3	0.46	0.68	0.88	0.99	0.68	0.87	0.97	1.00
France																	
1983–1984	1.85	8.42	1.28	1.25	17.0	9.18	2.02	13.3	13.6	0.48							
1985–1989	2.99	13.58	1.75	1.69	13.2	4.42	0.97	7.56	7.83	0.31							
1990–1994	(2.05)		1.00	1.00	8.47	4.13		8.48	8.48	0.18	0.31	0.60	0.86				

Table 3 (continued)

Country / area and period	*Annual [c] amount of ore extracted (kt U)*	*Equivalent amount of energy (GW a)*	*Monitored workers [d] (thousands)*	*Measurably exposed workers (thousands)*	*Annual collective effective dose*			*Average annual effective dose (mSv)*		*Distribution ratio (number of workers)*				*Distribution ratio (collective dose)*			
					Total [d] (man Sv)	*Average per unit uranium extracted (man Sv per kt)*	*Average per unit energy generated (man Sv per GW a)*	*Monitored workers*	*Measurably exposed workers*	NR_{15}	NR_{10}	NR_5	NR_1	SR_{15}	SR_{10}	SR_5	SR_1
Gabon																	
1985 - 1989	(0.90)		0.24		5.06			21.0									
1990 - 1994	0.60	2.72	0.19		2.58	4.30	0.95	13.4		0.36	0.55	0.72	0.88				
Germany [k]																	
1975 - 1979	6.26	28.5	14.7	14.7	160	25.5	5.61	10.9	10.9	0.46				0.72			
1980 - 1984	4.73	21.5	15.1	15.1	147	31.0	6.82	9.69	9.69	0.42				0.65			
1985 - 1989	4.07	18.5	16.1	1.61	133	32.7	7.18	8.24	8.24	0.31				0.57			
1990 - 1994	0.77	3.48	4.71	4.68	20.2	26.4	5.82	4.30	4.33	0.05	0.16	0.42	0.82	0.13	0.35	0.71	0.96
India [l]																	
1981 - 1984	0.13	0.58	1.16		13.8	108	23.7	11.9									
1985 - 1989	0.15	0.68	1.35		15.2	101	22.3	11.3									
1990 - 1994	(0.18)		[0.43]		[8.1]												
Slovenia [m]																	
1990 - 1994	0.01	0.05	0.11	0.11	0.27	23.3	5.13	2.46	2.62	0.00	0.00	0.27	0.53	0.00	0.00	0.61	0.87
Spain																	
1985 - 1989	0.36	1.64	0.38	0.23	0.26	0.71	0.15	0.68	1.14								
1990 - 1994	0.24	1.09	0.27	0.13	0.10	0.40	0.09	0.26	0.34	0.00	0.00	0.00	0.02	0.00	0.00	0.00	0.19
South Africa [n]																	
1975 - 1979	3.27	14.9	79.0		346	107	23.3	4.39									
1980 - 1984	5.07	23.0	93.6		399	78.8	17.3	4.27									
1985 - 1989	3.53	16.0	82.2		278	78.8	17.3	3.38									
1990 - 1994	(1.83)		[26]		[64]												
Russian Fed.																	
1985 - 1989								16.3									
1990 - 1994	(2.84)		2.89	2.89	6.39			2.21	2.21	0.01				0.09			
United States																	
1975 - 1979	5.51	25.1	6.85		30.9	5.60	1.23	4.51									
1980 - 1984	5.01	22.8	5.89	3.83	19.4	3.86	0.85	3.29	5.05								
1985 - 1989	2.27	10.3	0.77	0.62	2.68	1.18	0.26	3.46	4.33								
1990 - 1994	(2.22)		[0.25]		[1.2]												

Table 3 (continued)

Country / area and period	Annual [c] amount of ore extracted (kt U)	Equivalent amount of energy (GW a)	Monitored workers [d] (thousands)	Measurably exposed workers (thousands)	Annual collective effective dose			Average annual effective dose (mSv)		Distribution ratio (number of workers)				Distribution ratio (collective dose)			
					Total [d] (man Sv)	Average per unit uranium extracted (man Sv per kt)	Average per unit energy generated (man Sv per GW a)	Monitored workers	Measurably exposed workers	NR_{15}	NR_{10}	NR_5	NR_1	SR_{15}	SR_{10}	SR_5	SR_1
Total [o p]																	
1975 - 1979	22.7	103.3	116		643	28.3	6.25	5.54		0.39				0.69			
1980 - 1984	26.1	118.0	135		686	26.2	5.81	5.81		0.33				0.61			
1985 - 1989	30.3	136.2	116		509	16.8	3.74	4.40		0.26				0.53			
1990 - 1994	19.0	85.4	13.5	12.6	68.1	3.58	0.80	5.07	5.39	0.10	0.21	0.42	0.76	0.32	0.54	0.80	0.97
	[24.0]		[42.3]		[189]												
World [q]																	
1975 - 1979	52	240	240		1300	26	5.7	5.5		0.37				0.69			
1980 - 1984	64	290	310		1600	23	5.5	5.1		0.30				0.61			
1985 - 1989	59	270	260		1100	20	4.3	4.4		0.25				0.52			
1990 - 1995	39	180	69	62	310	7.9	1.72	4.5	5.0	0.10	0.21	0.42	0.76	0.32	0.54	0.80	0.97

a The data are annual averages over the periods indicated.
b Previously data for underground and open pit mines was presented separately. For this table the data for previous periods has been combined, as the 1990 - 1994 UNSCEAR survey made no distinction.
c Where countries did not report the amount of ore extracted, the value quoted in [O3] is given in round brackets. Where other significant data was missing, the Committee made estimates given in square brackets. These estimates based on the average trends for countries reporting for both 1985 - 1989 and 1990 - 1994.
d In the absence of reported data for 1990 - 1995 the Committee has estimated numbers of monitored workers and collective dose on the basis of the overall trend for those countries reporting for both 1985 - 1989 and 1990-1995. See also footnote *c*.
e Data contain a contribution from uranium milling.
f Part of Canada's production goes to the United States of America where it is used in reactors that have a different burn rate than the CANDU reactors used in Canada.
g For 1975 - 1983 the reported data contain a contribution from milling.
h Reported data from before 1981 did not include external radiation; an external dose of 2.6 mSv (the average external dose to monitored workers in 1982 - 1983) has been added here to reported doses before 1981. The reported distribution ratios before 1981 did not take account of external exposure and are therefore underestimates.
i Data for 1985 - 1989 are for Czechoslovakia.
j Exposures from inhalation of dust are not included; measurements have indicated that it would contribute less than 3 mSv to the annual committed effective dose.
k The 1975 - 1989 data is from the German Democratic Republic. During the period reported many of the mining operations in Germany were closed down; reducing the amount of ore extracted from 2.97 kt in 1990 to 0.05 kt in 1994.
l The contribution from the dust is very small because of the low grade of the ore and has been ignored.
m Uranium mining occurred for only six months in 1990; since then, further exposures have been from maintenance work only.
n Data are for gold mines. In 5 mines out of 40, uranium is produced as a by-product. The numbers of workers and total and normalized collective doses are those that can be attributed to uranium mining. Estimates of dose have been made for the whole workforce from measurements and knowledge of working environments. This average dose has been assumed for the period, and the tabulated collective doses are the product of this dose and the reported annual number of workers.
o These data should be interpreted with care, particularly when comparisons are made between different periods, as the countries included in the respective summations may differ from one period to another. The distribution ratios are averages of those reported, and the data on these are often less complete than data for the other quantities.
p The first line of the 1990 - 1994 value is for those countries that reported data for this period and excludes countries for which the Committee deemed it necessary to make estimates. The second line of the 1990 - 1994 values includes the estimates made Committee for China, India, South Africa and the United States.
q For 1990 - 1994 the worldwide estimates are extrapolated from the total amount of uranium mined worldwide relative to the sum of the total for which the Committee made an estimate.

Table 4
Exposures to workers from uranium milling [a b]
Data from UNSCEAR Survey of Occupational Exposures

Country / area and period	Annual amount of ore refined (kt U)	Equivalent amount of energy [c] (GW a)	Monitored workers (thousands)	Measurably exposed workers (thousands)	Annual collective [d] effective dose			Average annual effective dose (mSv)		Distribution ratio (number of workers)				Distribution ratio (collective dose)			
					Total (man Sv)	Average per unit uranium refined (man Sv per kt)	Average per unit energy generated (man Sv per GW a)	Monitored workers	Measurably exposed workers	NR_{15}	NR_{10}	NR_5	NR_1	SR_{15}	SR_{10}	SR_5	SR_1
Australia																	
1988–1989	4.20	19.1	0.61	0.61	2.04	0.49	0.11	3.36	3.36	0.00				0.00			
1991–1994			0.45	0.35	0.19			0.43	0.55	0.00	0.00	0.00	0.14	0.02	0.02	0.04	0.59
Canada [e]																	
1975–1979	4.31	19.6	0.668	0.458	0.66	0.153	0.034	0.99	1.44								
1980–1984	5.50	25.0	0.852	0.356	0.37	0.067	0.015	0.43	1.04								
1985–1989	9.29	42.2	0.83	0.66	1.30	0.14	0.031	1.56	1.95	0.01				0.01			
1990–1994			0.35	0.32	0.64			1.84	2.03	0.00	0.00	0.04	0.67	0.00	0.01	0.12	0.77
China																	
1985–1989			3.05		9.67			3.17									
Czechoslovakia [f]																	
1980–1984	1.82	8.27	1.13		11.4	6.28	1.38	10.1									
1985–1989	1.81	8.24	1.19		11.6	6.42	1.41	9.74									
France [g]																	
1988–1989	2.77	12.6	0.34	0.33	2.04	0.74	0.16	5.43	6.28								
German Dem.Rep. [h]																	
1975–1979	5.47	24.9	3.45	3.45	43.8	8.00	1.76	12.7	12.7								
1980–1984	4.60	20.9	3.24	3.24	34.1	7.40	1.63	10.5	10.5								
1985–1989	4.07	18.5	2.99	2.99	24.8	6.10	1.34	8.30	8.30								
India [i]																	
1981–1984	0.128	0.58	0.49		3.58	27.9	6.15	7.35									
1985–1989	0.150	0.68	0.58		3.40	22.6	4.97	5.86									
South Africa																	
1979	3.60	16.4	0.388	0.085	0.07	0.018	0.004	0.17	0.78								
1980–1984	4.46	20.3	0.648	0.277	1.93	0.432	0.095	2.97	6.95								
1985–1989	3.00	13.7	0.643	0.257	1.08	0.360	0.079	1.68	4.20								

Table 4 (continued)

Country / area and period	Annual amount of ore refined (kt U)	Equivalent amount of energy [c] (GW a)	Monitored workers (thousands)	Measurably exposed workers (thousands)	Annual collective [d] effective dose			Average annual effective dose (mSv)		Distribution ratio (number of workers)				Distribution ratio (collective dose)			
					Total (man Sv)	Average per unit uranium refined (man Sv per kt)	Average per unit energy generated (man Sv per GW a)	Monitored workers	Measurably exposed workers	NR_{15}	NR_{10}	NR_5	NR_1	SR_{15}	SR_{10}	SR_5	SR_1
United States																	
1975–1979	8.90	40.5	0.30	0.1	0.03	0.004	0.001	0.11	0.34								
1980–1984	16.8	76.4	4.80	3.0	4.48	0.267	0.059	0.93	1.49								
1985–1989	4.30	19.6	1.00	0.6	0.95	0.221	0.049	0.95	1.59								
Total																	
1975–1979	18.7	85	4.4		44.5	2.38	0.52	10.1									
1980–1984	28.8	131	10.4		53.2	1.85	0.41	5.1									
1985–1989	22.4	102	6.98		43.7	1.95	0.43	6.30		0.18				0.43			
1990–1994			0.80	0.66	0.83			1.04	1.25	0.00	0.00	0.02	0.37	0.01	0.01	0.08	0.68
World [j]																	
1975–1979	53	240	12		124	2.36	0.52	10.1									
1980–1984	64	290	23		117	1.84	0.41	5.1									
1985–1989	58	260	18		116	2.01	0.44	6.3									
1990–1994	39	180	6		20	0.5	0.11	3.3									

a The data are annual averages over the periods indicated.
b There is insufficient data to make a world estimate.
c Estimated on the simplifying assumption that all the milled uranium is used in LWRs. The assumed fuel cycle requirement is 220 t uranium $(GW\ a)^{-1}$.
d Doses from inhalation of radon daughters estimated using a conversion factor of 5.0 mSv WLM^{-1}.
e For 1975–1983, the quoted values are for extraction only; data for milling for this period are reported together with the mining data.
f Contribution from internal exposure is small and has not been explicitly estimated.
g The contribution from radon also includes the contribution from inhalation of ore dust.
h Doses estimated on basis of grab samples.
i The contribution of dust is small because of the low grade of the ore and has been ignored
j The worldwide estimate is based on the amount of ore refined being equal to the amount mined and on the downward trends for monitored workers and collective dose shown in Australia and Canada for the periods 1985–1989 to 1990–1994.

Table 5
Exposures to workers from uranium enrichment and conversion [a]
Data from UNSCEAR Survey of Occupational Exposures

Country / area and period	Annual amount of separative work (MSWU)	Electrical energy equivalent of uranium [b] (GW a)	Monitored workers (thousands)	Measurably exposed workers (thousands)	Annual collective effective dose			Average annual effective dose (mSv)		Distribution ratio (number of workers)				Distribution ratio (collective dose)			
					Total (man Sv)	Average per unit uranium enriched (man Sv per MSWU)	Average per unit energy generated (man Sv per GW a)	Monitored workers	Measurably exposed workers	NR_{15} [c]	NR_{10}	NR_5	NR_1	SR_{15}	SR_{10}	SR_5	SR_1
Canada [d]																	
1990–1994			0.33	0.22	0.29			0.88	1.32	0.00	0.00	0.02	0.30	0.00	0.01	0.16	0.81
France																	
1979			2.36	0.068		0.037		0.016	0.54								
1980–1984			2.33	0.050		0.035		0.015	0.69								
1985–1989			1.77	0.01	0.003			0.002	0.37	0.00							
1990–1994			4.04	0.17	0.08			0.02	0.44	0.00	0.00	0.00	0.04				
Japan																	
1987–1989	0.2		0.140		0												
1990–1994			3.60		0.06			0.00									
Netherlands																	
1985–1989			0.01		0.01												
1990–1994			0.08	0.06	0.02			0.28	0.36	0.00	0.00	0.00	0.06	0.00	0.00	0.00	0.33
South Africa																	
1985–1989	0.10		0.09		0.035	0.34	0.044	0.38									
1990–1994			0.31	0.26	0.25			0.81	0.91	0.00	0.00	0.01	0.28	0.00	0.02	0.07	0.67
United Kingdom																	
1975–1979			0.35		0.040			0.12									
1980–1984	0.06	0.47	0.22		0.049	0.665	0.086	0.22									
1985–1989	0.29	2.23	0.16		0.023	0.170	0.022	0.15									
1990–1994	0.63	5.11	0.77		0.15	0.037	0.005	0.20									
United States																	
1975–1979 [d]			10.3	8.34	5.14			0.50	0.62								
1980–1984			1.45	0.65	0.62			0.42	0.94								
1985–1989			2.92	0.93	0.36			0.12	0.38								
1990–1994 [e]			3.42	1.14	0.43			0.12	0.37								

Table 5 (continued)

Country / area and period	Annual amount of separative work (MSWU)	Electrical energy equivalent of uranium [b] (GW a)	Monitored workers (thousands)	Measurably exposed workers (thousands)	Annual collective effective dose			Average annual effective dose (mSv)		Distribution ratio (number of workers)				Distribution ratio (collective dose)			
					Total (man Sv)	Average per unit uranium enriched (man Sv per MSWU)	Average per unit energy generated (man Sv per GW a)	Monitored workers	Measurably exposed workers	NR_{15} [c]	NR_{10}	NR_5	NR_1	SR_{15}	SR_{10}	SR_5	SR_1
Total [f]																	
1975–1979			11		5.3			0.46		0.00				0.00			
1980–1984			4.3		0.78			0.18		0.00	0.00	0.00	0.08	0.00	0.02	0.12	0.73
1985–1989			5.0		0.43			0.08		0.00							
1990–1994			12.6		1.28			0.10		0.00							

a The data are annual averages over the periods indicated.
b Estimated on the simplifying assumption that all the enriched uranium is used in LWRs. The assumed fuel cycle requirement is 0.13 MSWU per GWa.
c The values are for the monitored workforce.
d Data relate to uranium refining.
e Data is taken from Department of Energy reports [D4].
f Total of reported data. These data should be interpreted with care particularly when making comparisons between different periods, as the countries included in the respective summation may differ from one period to another.

Table 6
Exposures to workers from fuel fabrication [a b]
Data from UNSCEAR Survey of Occupational Exposures

Country / area and period	Average annual production of fuel (kt U) [c]	Equivalent amount of energy [c d] (GW a)	Monitored workers (thousands)	Measurably exposed workers (thousands)	Annual collective effective dose			Average annual effective dose (mSv)		Distribution ratio (number of workers)				Distribution ratio (collective dose)			
					Total (man Sv)	Average per unit mass of fuel (man Sv per kt)	Average per unit energy generated (man Sv per GW a)	Monitored workers	Measurably exposed workers	NR_{15} [e]	NR_{10}	NR_5	NR_1	SR_{15}	SR_{10}	SR_5	SR_1
Argentina [f]																	
1980–1984	0.030	0.14	0.10		0.025	0.84	0.18	0.24									
1985–1989	0.046	0.21	0.11		0.024	0.51	0.11	0.22									
1990–1994	0.12	0.56	0.07	0.06	0.08	0.64	0.14	1.07	1.37	0.00	0.00	0.01	0.28	0.00	0.00	0.05	0.82
Canada																	
1975–1979	0.61	3.38	0.53	0.34	0.68	1.12	0.20	1.27	1.99	0.00				0.03			
1980–1984	1.13	6.30	0.65	0.36	0.95	0.84	0.15	1.48	2.64	0.00				0.00			
1985–1989	1.41	7.81	0.43	0.28	1.02	0.73	0.13	2.37	2.62	0.00				0.01			
1990–1994	1.57	(8.70)	0.33	0.22	0.66	0.42		2.01	3.01	0.00	0.01	0.15	0.47	0.00	0.06	0.51	0.96
China																	
1990–1994	0.02	0.31	1.17	1.13	1.33	87.6	4.33	1.13	1.18	0.00	0.00	0.04	0.30	0.00	0.00	0.23	0.79
France																	
1990–1994	(1.26)	(34.0)	0.58	0.30	1.50			2.59	5.03	0.04	0.08	0.17	0.52				
Japan																	
1979	0.83	14.5	1.44		0.69	0.83	0.05	0.48									
1980–1984	1.07	18.1	2.13		1.38	1.29	0.08	0.64									
1987–1989	1.29	20.7	2.61		0.67	0.52	0.03	0.26									
1990–1994	(1.01)	(16.2)	1.66	0.46	0.37			0.23	0.81	0.00	0.00	0.00	0.08	0.00	0.00	0.08	0.74
Russian Fed.																	
1992–1994	(1.95)			0.43	1.53		3.60	0.00									
South Africa																	
1990–1994	(0.10)		0.30	0.25	0.24			0.81	0.97	0.00	0.00	0.00	0.28	0.03	0.04	0.06	0.56
Spain [g]																	
1986–1989	0.16	4.43	0.35	0.25	0.38	2.53	0.09	1.09	1.53								
1990–1994	0.14	(3.88)	0.34	0.12	0.07	0.54		0.22	0.42	0.00	0.00	0.00	0.03	0.00	0.00	0.00	0.25
Sweden [h]																	
1986–1989	0.26	7.01	0.35	0.09	0.21	0.82	0.03	0.61	2.29								
1990–1994	0.30	(8.09)	0.37	0.08	0.05	0.18		0.15	0.68	0.00	0.00	0.00	0.04	0.00	0.04	0.04	0.58

Table 6 (continued)

Country / area and period	*Average annual production of fuel (kt U)* [c]	*Equivalent amount of energy* [c d] *(GW a)*	*Monitored workers (thousands)*	*Measurably exposed workers (thousands)*	*Annual collective effective dose*			*Average annual effective dose (mSv)*		*Distribution ratio (number of workers)*				*Distribution ratio (collective dose)*			
					Total (man Sv)	*Average per unit mass of fuel (man Sv per kt)*	*Average per unit energy generated (man Sv per GW a)*	*Monitored workers*	*Measurably exposed workers*	NR_{15} [e]	NR_{10}	NR_5	NR_1	SR_{15}	SR_{10}	SR_5	SR_1
U. Kingdom																	
1975–1979	1.39	14.5	2.56		5.79	4.17	0.40	2.26		0.00							
1980–1984	1.20	12.9	2.91		5.16	4.30	0.40	1.77		0.00							
1985–1989	1.27	14.7	2.96		8.99	7.08	0.61	3.04		0.02							
1990–1994	(1.20)	(13.9)	3.08		5.64			1.83									
United States																	
1975–1979	0.95	25.8	11.1	5.85	19.0	19.8	0.73	1.71	3.24	0.01				0.39			
1980–1984	1.19	32.3	9.45	5.49	8.68	7.26	0.27	0.92	1.58	0.00				0.12			
1985–1989	1.92	51.8	9.95	3.88	4.51	2.35	0.09	0.45	1.16	0.00				0.02			
1990-1994 [i]	(2.12)	(57.2)	9.58	3.66	5.66			0.59	0.71	0.00	0.01	0.02	0.12	0.20	0.58	0.80	0.96
Total																	
1975–1979	3.13	46.6	14.8		26.7	8.53	0.57	1.8									
1980–1984	4.64	69.9	15.6		16.2	3.49	0.23	1.04									
1985–1989	6.35	104	17.9		17.0	2.67	0.16	0.94									
1990-1994 [j]	8.79	143	16.2	8.3	16.8	1.91	0.12	1.03	2.02	0.00	0.01	0.03	0.16	0.11	0.31	0.55	0.89
World																	
1975–1979	3.6	60	20		36	10.0	0.59	1.8		0.01				0.38			
1980–1984	6.1	100	21		21	3.44	0.21	1.0		0.00				0.11			
1985–1989	9.67	180	28		22	2.28	0.12	0.78		0.00				0.02			
1990–1994	11.3	210	21	10.6	22	1.91	0.10	1.03	2.02	0.00	0.01	0.03	0.16	0.11	0.31	0.55	0.89

a The data are annual averages over the periods indicated.
b The data in previous reports covered the different types of fuel separately. For this report the previous data for 1975–1989 has been aggregated for all fuel types.
c Where no values were reported for average annual production of fuel it has been assumed that the value equals the fuel requirements of that country. The data for this has been taken from OECD [O8, O9] and IAEA [I20, I21]. These estimates are shown in parentheses.
d The amounts of fuel required to generate 1 GW a of electrical energy by each reactor type are taken to be as follows: PWR: 37 t; HWR: 180 t; Magnox: 330 T; AGR 38 t.
e The values are for the monitored workforce.
f Contribution from internal exposure not included but estimated to be less than 10%.
g Calculation of distribution ratios based on data for 1993 and 1994.
h Data on average annual production relates to kt of UO_2.
i Calculation for SR distribution ratios based on data from 1993 and 1994.
j The total number reported for measurably exposed workers has been increased pro rata to the data for monitored workers to allow for those countries reporting a collective dose but not the number of measurably exposed workers.

Table 7
Exposures to workers from reactor operation [a]
Data from UNSCEAR Survey of Occupational Exposures

Country / area and period	Average number of reactors over the period	Average annual energy generated (GW a)	Monitored workers (thousands)	Measurably exposed workers (thousands)	Annual collective effective dose			Average annual effective dose (mSv)		Distribution ratio (number of workers)				Distribution ratio (collective dose)			
					Total (man Sv)	Average per reactor (man Sv)	Average per unit energy generated (man Sv per GW a)	Monitored workers	Measurably exposed workers	NR_{15}	NR_{10}	NR_5	NR_1	SR_{15}	SR_{10}	SR_5	SR_1
PWRs																	
Belgium																	
1975–1979	4.0	1.14	2.39		5.28	1.32	4.63	2.21									
1980–1984	5.2	2.01	4.50		10.1	1.94	5.00	2.24									
1985–1989	7.6	4.26	8.38		17.9	2.36	4.22	2.14									
1990–1994	7.0	4.82			9.61	1.37	1.99										
Brazil																	
1990–1994	1.0		1.03	0.39	0.93	0.93		0.90	2.39	0.00	0.01	0.06	0.21	0.04	0.19	0.52	0.92
Bulgaria																	
1990–1994	5.8	1.57	2.29		12.2	2.10	7.77	5.33									
China																	
1992–1994	1.67	0.56	0.82	0.46	0.43	0.26	0.75	0.52	0.92	0.00	0.01	0.02	0.10	0.09	0.15	0.33	0.65
China, Taiwan																	
1984	1.0	0.34	3.68		0.26	0.26	0.77	0.07									
1985–1989	2.0	1.06	2.52		1.41	0.71	1.34	0.56									
1990–1994	2.0	1.48	1.94	1.42	2.12	1.06	1.43	1.09	1.49	0.01	0.03	0.06	0.19	0.29	0.43	0.62	0.90
Czech Rep. [b]																	
1975–1977	1.0	0.11	0.87	0.08	0.09	0.09	0.79	0.10	1.17	0.00				0.12			
1980–1989	2.2	0.62	1.56	0.80	1.84	0.83	2.97	1.18	2.30	0.01				0.17			
1985–1989	7.0	2.11	4.14	2.43	3.97	0.57	1.88	0.96	1.64	0.01				0.12			
1990–1994	4.0	1.25	2.36	1.20	1.47	0.37	1.17	0.63	1.11	0.00	0.00	0.02	0.12	0.03	0.07	0.20	0.59
Finland																	
1977–1979	1.0	0.34	0.93	0.47	0.79	0.79	2.31	0.84	1.69								
1980–1984	1.8	0.67	1.26	0.73	1.80	1.00	2.71	1.43	2.48	0.01				0.07			
1985–1989	2.0	0.84	1.09	0.65	1.73	0.87	2.05	1.59	2.66	0.01				0.07			
1990–1994	2.0	0.77	1.24	0.77	2.45	1.23	3.20	1.97	3.19	0.01	0.05	0.14	0.38	0.12	0.32	0.64	0.95

Table 7 (continued)

Country / area and period	Average number of reactors over the period	Average annual energy generated (GW a)	Monitored workers (thousands)	Measurably exposed workers (thousands)	Annual collective effective dose: Total (man Sv)	Annual collective effective dose: Average per reactor (man Sv)	Annual collective effective dose: Average per unit energy generated (man Sv per GW a)	Average annual effective dose (mSv): Monitored workers	Average annual effective dose (mSv): Measurably exposed workers	Distribution ratio (number of workers): NR_{15}	NR_{10}	NR_5	NR_1	Distribution ratio (collective dose): SR_{15}	SR_{10}	SR_5	SR_1
France																	
1977–1979	3.5	1.93	3.40	0.89	4.34	1.24	2.24	1.28	4.87								
1980–1984	17.2	11.1	14.4	6.40	29.4	1.71	2.65	2.05	4.60	0.03							
1985–1989	41.0	28.3	29.7	16.8	78.9	1.92	2.79	2.65	4.68	0.05							
1990–1994	52.0	38.3			113	2.17	2.95										
Germany [c]																	
1975–1979	8.8	3.31	7.32		22.2	4.92	14.9	5.97		0.04				0.45			
1980–1984	11.6	6.34	11.7		43.0	6.94	13.3	6.79		0.06				0.44			
1985–1989	16.4	10.9	19.0	1.58	41.8	4.71	10.3	4.58	5.85	0.05				0.42			
1990–1994	14.0	12.5			27.1	1.94	2.17										
Hungary																	
1983–1984	0.5	0.36	1.26	0.29	0.32	0.21	0.89	0.25	1.09								
1985–1989	3.4	1.19	2.81	0.99	1.70	0.50	1.43	0.61	1.72	0.00				0.05			
1990–1994	4.0	1.58	3.46	1.06	2.92	0.73	1.84	0.84	2.74	0.01	0.02	0.05	0.18	0.11	0.26	0.57	0.93
Japan																	
1975–1979	7.0	2.02	7.21	6.11	14.1	2.02	6.99	1.96	2.32	0.02				0.18			
1980–1984	11.8	5.44	13.2	9.22	30.7	2.60	5.65	2.32	3.33	0.02				0.16			
1985–1989	16.2	9.22	18.6	12.1	33.5	2.07	3.63	1.80	2.76	0.01				0.12			
1990–1994	20.2	10.88	22.6	12.7	26.4	1.30	2.42	1.17	2.08	0.00	0.02	0.07					
Netherlands																	
1975–1979	1.0	0.37	0.60		4.10	4.10	11.0	6.89		0.14				0.44			
1980–1984	1.0	0.39	0.96		3.58	3.58	9.24	3.75		0.06				0.30			
1985–1989	1.0	0.39	1.14		2.83	2.83	7.21	2.48		0.02				0.15			
1990–1994	2.0	0.40	1.77	1.25	2.59	1.30	6.47	1.47	2.07	0.00	0.02	0.09	0.34	0	0.15	0.51	0.92
Peru 1994	1.0		0.03	0.03	0.02	0.02		0.45	0.52	0	0	0	0.03				
Slovakia																	
1990–1994	4.0	1.31	1.39	1.39	2.74	0.68	2.09	1.97	1.97	0.00	0.02	0.12	0.45	0.02	0.13	0.49	0.90
Slovenia																	
1990–1994	1.0	0.48	0.69	0.69	1.40	1.40	2.92	2.04	2.04	0.01	0.07	0.13	0.41	0.10	0.27	0.59	0.92

Table 7 (continued)

Country / area and period	Average number of reactors over the period	Average annual energy generated (GW a)	Monitored workers (thousands)	Measurably exposed workers (thousands)	Annual collective effective dose			Average annual effective dose (mSv)		Distribution ratio (number of workers)				Distribution ratio (collective dose)			
					Total (man Sv)	Average per reactor (man Sv)	Average per unit energy generated (man Sv per GW a)	Monitored workers	Measurably exposed workers	NR_{15}	NR_{10}	NR_5	NR_1	SR_{15}	SR_{10}	SR_5	SR_1
South Africa																	
1984	2.0	0.45	1.72	0.08	0.12	0.06	0.27	0.07	1.45	0.00				0.29			
1985-1989	2.0	0.96	1.72	0.59	1.61	0.81	1.68	0.94	2.75	0.01				0.18			
1990-1994	2.0	1.06	1.79	0.77	2.07	1.03	1.95	1.15	2.70	0.01	0.03	0.07	0.23	0.13	0.31	0.60	0.93
Spain [d]																	
1975-1979	1.0	0.13	0.22		2.60	2.60	20.7	11.7									
1980-1984	2.6	0.67	1.51		6.76	2.60	10.1	4.21									
1985-1989	5.6	3.25	5.30	3.81	17.7	3.17	5.45	3.35	4.65								
1990-1994	7.0	5.01	6.85	4.53	12.9	1.85	2.58	1.88	2.46	0.01	0.03	0.09	0.31	0.13	0.30	0.57	092
Sweden																	
1975-1979	1.0	0.47		0.62	1.52	1.52	3.28		2.46	0.03				0.24			
1980-1984	2.2	0.87		0.97	3.58	1.63	4.10		3.68	0.03				0.27			
1985-1989	3.0	1.93		1.82	4.80	1.60	2.49		2.65	0.03				0.19			
1990-1994	3.0	2.13			2.70	0.90	1.27							0.19			
Switzerland																	
1975-1979	2.2	0.71	0.63		4.16	1.89	5.83	6.64									
1980-1984	3.0	1.44	1.49		7.46	2.49	5.20	5.01									
1985-1989	3.0	1.44	1.67		6.60	2.20	4.58	3.95									
1990-1994	3.0	1.50	2.15		4.11	1.37	2.74	1.91		0.01	0.04	0.13	0.37	0.10	0.26	0.60	0.92
United States [e]																	
1975-1979	34.2	16.2	38.8	22.8	147	4.31	9.13	3.80	6.47	0.09				0.57			
1980-1984	46.8	22.1	83.1	51.0	276	5.89	12.5	3.32	5.41	0.08				0.53			
1985-1989	63.0	37.4	109.2	61.4	225	3.58	6.02	2.06	3.67	0.04				0.36			
1990-1994	72.6	51.5	114.1	58.0	154	2.12	2.99	1.35	0.31	0.00	0.03	0.09	0.27	0.01	0.13	0.42	0.91
USSR																	
1978-1979	7.5	1.7	3.2		19.4	2.59	11.2	6.14									
1980-1984	12.8	3.8	6.6		32.8	2.56	8.66	4.99									
1985-1987	22.0	8.7	12.3		57.1	2.60	6.55	4.63									
(Russian Fed.)																	
1985-1989	22.0	8.7	12.3		57.1	2.60	6.55	4.63									
1990-1994			10.5		29.2												

Table 7 (continued)

Country / area and period	Average number of reactors over the period	Average annual energy generated (GW a)	Monitored workers (thousands)	Measurably exposed workers (thousands)	Annual collective effective dose: Total (man Sv)	Annual collective effective dose: Average per reactor (man Sv)	Annual collective effective dose: Average per unit energy generated (man Sv per GW a)	Average annual effective dose (mSv): Monitored workers	Average annual effective dose (mSv): Measurably exposed workers	Distribution ratio (number of workers): NR_{15}	NR_{10}	NR_5	NR_1	Distribution ratio (collective dose): SR_{15}	SR_{10}	SR_5	SR_1
Total [f]																	
1975-1979	64.4	26.1	60.9		212	3.29	8.13	3.48		0.09				0.56			
1980-1984	121	56.3	144		451	3.73	8.01	3.14		0.06				0.48			
1985-1989	192	112	219		487	2.53	4.36	2.22		0.03				0.32			
1990-1994	209.3	137	260	140	380	1.82	2.78	1.45	2.61	0.00	0.02	0.08	0.27	0.07	0.21	0.51	0.90
World																	
1975-1979	78	27	63		220	2.8	8.1	3.5		0.09				0.56			
1980-1984	140	56	140		450	3.3	8.0	3.1		0.06				0.48			
1985-1989	220	120	230		500	2.3	4.3	2.2		0.03				0.32			
1990-1994	242	149	310	166	415	1.72	2.78	1.34	2.51	0.00	0.02	0.28	0.27	0.07	0.21	0.51	0.90
B W R s																	
China, Taiwan																	
1981-1984	3.8	1.83	6.32		14.4	3.84	7.85	2.28									
1985-1989	4.0	2.32	6.69		18.2	4.55	7.84	2.72									
1990-1994	4.0	2.39	6.17	4.92	13.56	3.39	5.69	2.20	2.76	0.03	0.06	0.13	0.32	0.37	0.53	0.73	0.95
Finland																	
1978-1979	1.0	0.21	1.44	0.29	0.12	0.12	0.55	0.08	0.40								
1980-1984	2.0	1.02	1.61	0.88	0.87	0.44	0.86	0.54	0.99	0.00				0.00			
1985-1989	2.0	1.33	1.92	1.14	1.80	0.90	1.36	0.94	1.59	0.00				0.03			
1990-1994	2.0	1.33	2.12	1.18	1.87	0.94	1.41	0.88	1.59	0.00	0.01	0.04	0.23	0.02	0.14	0.37	0.85
Germany [c]																	
1975-1979	3.0	0.72	3.74		19.9	6.64	27.8	5.33									
1980-1984	4.4	2.12	10.2		33.4	7.59	15.7	3.28									
1985-1989	7.0	5.68	12.4		19.4	2.78	3.42	1.56									
1990-1994	7.0	4.82			15.6	2.23	3.24										
India																	
1980-1984	2.0	0.20	3.35	3.30	38.0	19.0	189	11.4	11.5	0.24							
1985-1989	2.0	0.21	2.69	2.56	23.2	11.6	113	8.63	9.06	0.16							
Japan																	
1975-1979	7.8	2.30	18.2	17.7	72.9	9.35	31.6	4.01	4.12	0.07				0.34			
1980-1984	13.0	6.24	27.4	18.9	91.4	7.03	14.6	3.34	4.83	0.06				0.34			
1985-1989	18.4	10.6	34.8	20.7	63.6	3.46	6.02	1.83	3.07	0.02				0.20			
1990-1994	23.4	13.5	39.6	20.6	44.3	1.89	3.30	1.12	2.15	0.01	0.01	0.04					

Table 7 (continued)

Country / area and period	Average number of reactors over the period	Average annual energy generated (GW a)	Monitored workers (thousands)	Measurably exposed workers (thousands)	Annual collective effective dose			Average annual effective dose (mSv)		Distribution ratio (number of workers)				Distribution ratio (collective dose)			
					Total (man Sv)	Average per reactor (man Sv)	Average per unit energy generated (man Sv per GW a)	Monitored workers	Measurably exposed workers	NR_{15}	NR_{10}	NR_5	NR_1	SR_{15}	SR_{10}	SR_5	SR_1
Mexico																	
1990-1994	1.0	0.49			4.64	4.64	9.40										
Netherlands																	
1975-1979	1.0	0.05	0.28		2.31	2.31	49.2	8.38		0.20				0.24			
1980-1984	1.0	0.05	0.47		2.24	2.24	48.1	4.81		0.11				0.27			
1985-1989	1.0	0.05	0.56		1.62	1.62	32.9	2.87		0.04				0.19			
Spain [d]																	
1975-1979	1.0	0.32	0.62		5.36	5.36	16.8	8.60									
1980-1984	1.2	0.27	0.97		7.85	6.54	29.2	8.08									
1985-1989	2.0	1.09	2.66	2.06	10.1	5.05	9.26	3.80	4.90								
1990-1994	2.0	1.20	2.87	2.24	7.74	3.87	6.43	2.70	3.01	0.01	0.04	0.15	0.47	0.05	0.22	0.57	0.95
Sweden																	
1975-1979	4.6	1.64		2.09	5.98	1.3	3.65		2.86	0.03				0.24			
1980-1984	6.6	3.46		3.13	8.22	1.25	2.38		2.63	0.03				0.27			
1985-1989	9.0	5.64		3.71	10.7	1.19	1.89		2.88	0.03				0.19			
1990-1994	9.0	5.70			15.8	1.76	2.77										
Switzerland																	
1990-1994	2.0	1.18	2.58		3.97	1.99	3.36	1.54		0.01	0.02	0.09	0.33	0.06	0.21	0.53	0.91
United States [e]																	
1975-1979	22.8	9.37	33.3	19.9	156	6.83	16.6	4.68	7.84	0.06				0.65			
1980-1984	26.2	10.4	53.3	35.1	268	10.2	25.7	5.03	7.63	0.08				0.63			
1985-1989	32.2	14.7	77.2	40.5	181	5.63	12.3	2.35	4.48	0.03				0.43			
1990-1994	37.0	21.5	76.6	40.1	131	3.54	6.08	1.71	3.27	0.00	0.04	0.12	0.30	0.14	0.28	0.62	0.94
Total																	
1975-1979	40.6	14.3	55.9		262	6.46	18.1	4.69		0.07				0.61			
1980-1984	59.0	25.2	102		454	7.69	18.0	4.47		0.08				0.55			
1985-1989	77.6	41.6	139		330	4.25	7.93	2.38		0.03				0.36			
1990-1994	87.4	52.1	160	87.0	238	2.73	4.58	1.56		0.01	0.04	0.12	0.31	0.13	0.33	0.63	0.94
World																	
1975-1979	51.2	15.3	59.2		279	5.45	18.3	4.71		0.07				0.61			
1980-1984	64.6	25.1	102		454	7.00	18.0	4.47		0.08				0.55			
1985-1989	83.8	41.8	139		331	3.96	7.94	2.38		0.03				0.36			
1990-1994	90.0	50.4	160	87.0	240	2.67	4.76	1.57	2.86	0.00	0.04	0.12	0.31	0.13	0.33	0.63	0.94

Table 7 (continued)

Country / area and period	Average number of reactors over the period	Average annual energy generated (GW a)	Monitored workers (thousands)	Measurably exposed workers (thousands)	Annual collective effective dose: Total (man Sv)	Annual collective effective dose: Average per reactor (man Sv)	Annual collective effective dose: Average per unit energy generated (man Sv per GW a)	Average annual effective dose (mSv): Monitored workers	Average annual effective dose (mSv): Measurably exposed workers	Distribution ratio (number of workers): NR_{15}	NR_{10}	NR_5	NR_1	Distribution ratio (collective dose): SR_{15}	SR_{10}	SR_5	SR_1
HWRs																	
Argentina																	
1975-1979	1.0	0.26	0.43		4.52	4.52	17.2	10.5		0.26				0.73			
1980-1984	1.4	0.32	0.77		8.04	5.74	25.2	10.5		0.27				0.79			
1985-1989	2.0	0.61	1.06		12.6	6.29	20.8	11.9		0.29				0.80			
1990-1994	2.0	0.87	1.47	1.26	12.0	6.01	13.8	8.17	9.54	0.20	0.27	0.41	0.66	0.65	0.77	0.90	0.99
Canada																	
1975-1979	8.4	2.45	5.65	2.62	24.0	2.85	9.77	4.24	9.15	0.11				0.70			
1980-1984	13	4.53	9.27	3.54	20.1	1.57	4.43	2.16	5.67	0.05				0.49			
1985-1989	18	8.03	11.0	4.61	16.7	0.94	2.07	1.51	3.61	0.02				0.23			
1990-1994	22.0	8.63	15.0	5.05	15.9	0.72	1.66	1.06	3.15	0.01	0.02	0.07	0.22	0.11	0.22	0.59	0.93
Czechoslovakia [a]																	
1975-1979	1.0		0.85	0.65	4.61	4.61		5.42	7.03	0.11				0.58			
1980-1984	1.0		0.51	0.36	0.77	0.77		1.51	2.13	0.02				0.22			
1985-1989	1.0		0.54	0.31	0.88	0.88		1.62	2.83	0.02				0.24			
Japan																	
1990-1994	1.0	0.11	1.79	1.11	3.28	3.28	29.06	1.84	2.96	0.01	0.04	0.12	0.36	0.09	0.29	0.61	0.94
Pakistan																	
1990-1994	1.0	0.48	0.65	0.54	1.87	1.87	3.92	2.89	3.23	0.02	0.07	0.20	0.51	0.14	0.32	0.65	0.95
Rep. of Korea																	
1983-1984	1.0	0.41	0.72		0.65	0.65	1.58	0.90									
1985-1989	1.0	0.59	0.81		1.13	1.13	1.91	1.40									
Total																	
1975-1979	9.40	2.71	6.08		28.5	3.03	10.5	4.68		0.12				0.71			
1980-1984	16.6	5.13	12.8		40.9	2.47	7.97	3.20		0.08				0.58			
1985-1989	25.0	9.61	17.3		59.0	2.36	6.14	3.41		0.07				0.48			
1990-1994	24.0	9.25	16.5	6.31	27.9	1.16	3.02	1.69	4.43	0.02	0.04	0.10	0.26	0.34	0.46	0.72	0.96
World																	
1975-1979	12	3.1	6.8		32	2.6	11	4.8		0.12				0.71			
1980-1984	19	5.7	14		46	2.4	8.0	3.2		0.07				0.58			
1985-1989	26	9.8	18		60	2.3	6.2	3.4		0.07				0.48			
1990-1994	31.2	11.6	20	7.90	35	1.1	3.0	1.74	4.35	0.02	0.04	0.10	0.26	0.34	0.46	0.72	0.96

Table 7 (continued)

Country / area and period	*Average number of reactors over the period*	*Average annual energy generated (GW a)*	*Monitored workers (thousands)*	*Measurably exposed workers (thousands)*	*Annual collective effective dose*			*Average annual effective dose (mSv)*		*Distribution ratio (number of workers)*				*Distribution ratio (collective dose)*			
					Total (man Sv)	*Average per reactor (man Sv)*	*Average per unit energy generated (man Sv per GW a)*	*Monitored workers*	*Measurably exposed workers*	NR_{15}	NR_{10}	NR_5	NR_1	SR_{15}	SR_{10}	SR_5	SR_1
G C R s																	
France																	
1990-1994	2.0	0.32			0.58	0.29	1.78										
Japan																	
1979	1.0	0.1	1.59	0.81	1.0	1.0	10	0.63	1.23	0.00							
1980-1984	1.0	0.1	2.13	0.95	1.0	1.0	10	0.47	1.05	0.00				0.02			
1985-1989	1.0	0.1	2.01	0.84	1.0	1.0	10	0.50	1.19	0.00				0.01			
1990-1994	1.0	0.08	1.74	0.54	0.42	0.42	4.99	0.24	0.78	0.00	0.00	0.01					
Spain																	
1975-1979	1.0	0.37	0.07		0.30	0.30	0.80	3.98									
1980-1984	1.0	0.36	0.18		0.37	0.37	1.02	2.08									
1985-1989	1.0	0.33	0.25	0.13	0.28	0.28	0.85	1.12	2.18								
1990-1994																	
United Kingdom																	
1975-1979	30.0	3.40	8.56		24.5	0.82	7.20	2.86		0.02							
1980-1984	32.0	4.40	18.0		26.4	0.82	6.00	1.46		0.00							
1985-1989	37.0	6.09	25.4		19.5	0.52	3.20	0.77		0.00							
1990-1991	36.0	7.72	26.4		15.0	0.42	1.94	0.57		0.00							
Total																	
1975-1979	31.2	3.79	8.95		25.0	0.80	6.59	2.80		0.02							
1980-1984	34.0	4.86	20.3		27.8	0.82	5.72	1.37		0.01							
1985-1989	39.2	6.52	27.6		20.8	0.53	3.19	0.75		0.00				0.01			
1990-1994	39	8.14			15.9	0.41	1.96										
World																	
1975-1979	40	5.4	13		36.0	0.90	6.6	2.8									
1980-1984	41	6.0	25		34.0	0.84	5.8	1.4									
1985-1989	44	7.4	31		24.0	0.54	3.2	0.75									
1990-1994	37.6	8.36	30		16.4	0.44	1.96	0.54									
L W G R s																	
Lithuania [g]																	
1990-1994	2				16.06	8.03											

Table 7 (continued)

Country / area and period	*Average number of reactors over the period*	*Average annual energy generated (GW a)*	*Monitored workers (thousands)*	*Measurably exposed workers (thousands)*	*Annual collective effective dose*			*Average annual effective dose (mSv)*		*Distribution ratio (number of workers)*				*Distribution ratio (collective dose)*			
					Total (man Sv)	*Average per reactor (man Sv)*	*Average per unit energy generated (man Sv per GW a)*	*Monitored workers*	*Measurably exposed workers*	NR_{15}	NR_{10}	NR_5	NR_1	SR_{15}	SR_{10}	SR_5	SR_1
Russian Fed. [h]																	
1990–1994	10.4				100.6	9.67											
Total																	
1990–1994	12.4				116.7	9.40											
World																	
1978–1979	12	4.35	5.37		35.6	2.97	8.18	6.64									
1980–1984	16.2	7.50	9.80		62.2	3.84	8.30	6.35									
1985–1987	20	10.4	13.1		173	8.67	16.7	13.2									
1990–1994	20	9.38			190	9.40	20.3										

a The data are annual averages over the periods indicated.
b Data for 1985–1989 are for Czechoslovakia.
c Data for 1985–1989 cover the Federal Republic of Germany and German Democratic Republic. Within the period 1990–1994, the data for 1990 relate to the Federal Republic of Germany.
d Calculation of distribution ratios based on data from 1993 and 1994.
e Calculation of SR distribution ratios based on data from 1993 and 1994.
f Excludes data from Russian Federation.
g Data was provided by ISOE database [L5].
h Data taken from Rosenergoatom Concern Annual Report [R2].

Table 8
Summary of worldwide exposures from reactor operation [a]

Reactor type	*Average number of reactors*	*Average annual energy generated* [b] *(GW a)*	*Monitored workers* [c] *(thousands)*	*Average annual collective effective dose* [d] *(man Sv)*	*Collective effective dose per reactor (man Sv)*	*Collective effective dose per unit energy generated (man Sv per GW a)*	*Average annual effective dose to monitored workers (mSv)*	*Annual average dose to measurably exposed workers (mSv)*	*Average annual value of* NR_{15} [e]	*Average annual value of* SR_{15}
					1975–1979					
PWR	78	27	63	220	2.8	8.1	3.5		0.085	0.56
BWR	51	15	59	280	5.45	18	4.7		0.066	0.61
HWR	12	3.1	6.8	32	2.6	11	4.8		0.12	0.71
LWGR [f]	12	4.4	5.4	36	2.97	8.2	6.6			
GCR	40	5.4	13	36	0.90	6.6	2.8		0.020	
HTGR [g]	1	0.03	1.2	0.03	0.03	0.90	0.03			
Total	190	55	150	600	3.2	11	4.1		0.078	0.60
					1980–1984					
PWR	140	56	140	450	3.3	8.0	3.1		0.061	0.48
BWR	65	25	100	450	7.00	18	4.5		0.079	0.55
HWR	19	5.7	14	46	2.4	8.0	3.2		0.073	0.58
LWGR	16	7.5	9.8	62	3.82	8.3	6.4			
GCR	41	6.0	25	34	0.82	5.8	1.4		0.005	
FBR	4	0.50	1.4	0.61	0.15	1.2	0.44			
HTGR	1	0.07	1.2	0.02	0.02	0.24	0.01			
Total	280	100	290	1000	3.6	10	3.5		0.069	0.52
					1985–1989					
PWR	220	120	230	500	2.3	4.3	2.2		0.034	0.32
BWR	84	42	140	330	3.96	7.9	2.4		0.026	0.36
HWR	26	10	18	60	2.3	6.2	3.4		0.066	0.48
LWGR [h]	20	10	13	170	8.67	17	13			
GCR	44	7.4	31	24	0.54	3.2	0.75		0.0002	0.01
FBR [i]	5	0.73	2.1	1.0	0.21	1.4	0.48			
HTGR	1	0.03	0.78	0.10	0.10	3.3	0.12			
Total	400	190	430	1100	2.8	5.9	2.5		0.033	0.34

Table 8 (continued)

Reactor type	*Average number of reactors*	*Average annual energy generated* [b] *(GW a)*	*Monitored workers* [c] *(thousands)*	*Average annual collective effective dose* [d] *(man Sv)*	*Collective effective dose per reactor (man Sv)*	*Collective effective dose per unit energy generated (man Sv per GW a)*	*Average annual effective dose to monitored workers (mSv)*	*Annual average dose to measurably exposed workers (mSv)*	*Average annual value of* NR_{15} [e]	*Average annual value of* SR_{15}
1990–1994										
PWR	242	149	310	415	1.7	2.8	1.3	2.5	0.00	0.07
BWR	90	50	160	240	2.7	4.8	1.6	2.9	0.00	0.13
HWR	31	12	20	35	1.1	3.0	1.7	4.4	0.02	0.34
LWGR	20	9.4		190	9.4	20.3				
GCR	38	8.4	30	16	0.4	2.0	0.5			
Total	421	230	530	900	2.1	3.9	1.4	2.7	0.00	0.08

a The data are annual values averaged over the respective five-year periods and are, in general, quoted to two significant figures.
b Values in parentheses are the percentage contributions, rounded to the nearest per cent, made by that reactor type to the total energy generated.
c Values in parentheses are the percentage contributions, rounded to the nearest per cent, made by that reactor type to the total number of monitored workers.
d Values in parentheses are the percentage contributions, rounded to the nearest per cent, made by that reactor type to the total collective effective dose.
e The values of the ratios, NR_{15} and SR_{15} are only indicative of worldwide levels. Data on these ratios are not available from all countries, and the tabulated values are averages of those data reported.
f Averages of 1978 and 1979 tabulated and assumed representative of whole period in absence of data for earlier years.
g Includes data for Fort St. Vrain only; insufficient data to extrapolate to other prototype HTGRs.
h Averages of 1985–1987 tabulated and assumed representative of whole period in absence of data for later years in period.
i Averaged over 1986, 1987 and 1989, as data for other years in period were unavailable.

Table 9
Collective effective doses to workers at reactors during replacement of steam generators
[O5]

Country	*Reactor*	*Replacement year*	*Number of loops replaced*	*Collective effective dose (man Sv)*	
				Per replacement	*Per loop*
Belgium	Doel 3	1993	3	1.96	0.65
France	Dampierre 1	1990	3	2.13	0.71
	Bugey 5	1993/1994	3	1.55	0.52
	Gravelines 1	1994	3	1.45	0.48
Germany	Obrigheim	1983	2	6.90	3.45
Japan	Mihama 2	1994	2	1.46	0.73
	Takahama 2	1994	3	1.49	0.50
Sweden	Ringhals 2	1989	3	2.90	0.97
Switzerland	Beznau 1	1993	2	1.10	0.55
United States	Surry 2	1979	3	21.4	7.14
	Surry 1	1980	3	17.6	5.86
	Turkey Point 3	1981	3	21.5	7.17
	Turkey Point 4	1982	3	13.1	4.35
	Point Beach 1	1983	2	5.90	2.95
	H.B. Robinson 2	1984	3	12.1	4.02
	D.C. Cook 2	1988	4	5.61	1.40
	Indian Point	1989	4	5.41	1.35
	Palisades	1990	3	4.87	1.62
	Millstone 2	1992	3	6.70	2.23
	North Anna 1	1993	3	2.40	0.80

Table 10
Exposures to workers from fuel reprocessing [a]
Data from UNSCEAR Survey of Occupational Exposures

Country / area and period	Average annual amount of fuel processed (kt U)	Electrical energy equivalent (GW a)	Monitored workers (thousands)	Measurably exposed workers (thousands)	Annual collective effective dose			Average annual effective dose (mSv)		Distribution ratio [b] (number of workers)				Distribution ratio (collective dose)			
					Total (man Sv)	Average per unit fuel generated (man Sv per kt)	Average per unit energy generated (man Sv per GW a)	Monitored workers	Measurably exposed workers	NR_{15}	NR_{10}	NR_5	NR_1	SR_{15}	SR_{10}	SR_5	SR_1
France																	
1975–1979	0.360	1.46	4.35	2.97	12.8			2.94	4.31	0.06				0.29			
1980–1984	0.375	3.87	6.70	3.89	14.1			2.10	3.62	0.01				0.11			
1985–1989	0.434	8.85	9.28	3.86	12.5			1.35	3.25	0.01				0.12			
1990–1994			13.0	3.31	4.72			0.36	1.43	0.00	0.00	0.01	0.26				
India																	
1981–1984			1.48	1.27	6.76			4.57	5.33	0.087				0.459			
1985–1989			1.66	1.32	5.53			3.34	4.19	0.046				0.308			
1990-1994 [c]			1.66	1.32	5.53												
Japan																	
1975–1979	0.010		0.84		0.38	38		0.44		0							
1980–1984	0.030		1.37		1.23	41		0.89		0.000							
1985–1989	0.052		1.87		1.83	35.2		0.98		0.01							
1990–1994	0.074	1.4	2.58	0.71	0.82	11.1	0.60	0.32	1.15	0.00	0.00	0.01	0.08	0.03	0.03	0.13	0.64
Netherlands																	
1990–1994			0.08	0.04	0.03			0.39	0.75	0.00	0.00	0.01	0.12	0.00	0.00	0.07	0.66
Russian Fed.																	
1990–1994			12.0	11.5	33.9			2.82	2.96					0.19			
United Kingdom																	
1977–1979	0.715	2.17	5.61		46.6	65	21.5	8.31		0.193							
1980–1984	0.970	2.94	6.62		40.1	41	13.6	6.05		0.143							
1985–1989	0.887	2.69	7.22		29.4	33	11.0	4.07		0.10							
1990–1994			10.2		20.7			2.03		0.00	0.03	0.12		0.08			
United States																	
1975–1979			2.65	2.05	10.8			4.06	5.27								
1980–1984			2.95	2.06	7.43			2.51	3.61								
1985–1989			3.21	1.78	4.89			1.52	2.74								
1990-1994 [d]			5.61	1.99	1.64			0.30	0.82								

Table 10 (continued)

Country / area and period	Average annual amount of fuel processed (kt U)	Electrical energy equivalent (GW a)	Monitored workers (thousands)	Measurably exposed workers (thousands)	Annual collective effective dose			Average annual effective dose (mSv)		Distribution ratio [b] (number of workers)				Distribution ratio (collective dose)			
					Total (man Sv)	Average per unit fuel generated (man Sv per kt)	Average per unit energy generated (man Sv per GW a)	Monitored workers	Measurably exposed workers	NR_{15}	NR_{10}	NR_5	NR_1	SR_{15}	SR_{10}	SR_5	SR_1
World [e]																	
1975–1979			7.5		53			7.07									
1980–1984			9.4		46			4.89									
1985–1989			17.0		36			2.46		0.047							
1990–1994			45	24	67			1.49	2.79					0.13			

a Data are annual averages over the indicated period.
b These values are based on the monitored workforce, and if not available on the measurably exposed workers.
c No data was reported for India for 1990–1994, therefore the Committee has assumed that data for the previous period are still a valid approximation.
d Reprocessing at United States Department of Energy facilities are mainly associated with defense activities rather than commercial fuel reprocessing [D4].
e Great care should be taken when trying to compare different time periods. In particular the world estimates for the time periods from 1975 to 1989 were based on the French and United Kingdom operations, as the other major contributor, the United States was considered to be more concerned with defense activities. The data for 1990–1994 covers all contributions and in particular a contribution from the Russian Federation which accounts for some 50% of the annual collective effective dose.

Table 11
Exposures to workers from research in the nuclear fuel cycle [a]
Data from UNSCEAR Survey of Occupational Exposures

Country / area	Period	Monitored workers (thousands)	Measurably exposed workers (thousands)	Annual collective effective dose (man Sv)	Average annual effective dose (mSv)		Distribution ratio (number of workers)				Distribution ratio (collective dose)			
					Monitored workers	Measurably exposed workers	NR_{15}	NR_{10}	NR_5	NR_1	SR_{15}	SR_{10}	SR_5	SR_1
Argentina	1975–1979	0.2	0.01	0.2	1.0	20								
	1980–1984	0.2	0.01	0.17	0.85	17								
	1985–1989	0.13	0.02	0.07	0.54	3.9								
	1990–1994	0.11	0.08	0.08	0.76	1.03	0.00	0.00	0.03	0.20	0.00	0.05	0.23	0.75
Canada [b]	1975–1979	4.49	3.94	13.5	2.95	3.36	0.01				0.44			
	1980–1984	4.56	4.30	11.1	2.43	2.57	0.04				0.41			
	1985–1989	4.20	3.97	6.1	1.45	1.54	0.03				0.40			
	1990–1994	4.12	3.25	6.0	1.46	1.85	0.02	0.04	0.07	0.25	0.23	0.39	0.54	0.78
Chile [c]	1975–1979	0.02	0.02	0.04	2.41	2.41	0.01				0.03			
	1980–1984	0.03	0.03	0.05	2.00	2.00	0.03				0.11			
	1985–1989	0.05	0.05	0.06	1.23	1.23	0.02				0.06			
China	1990–1994	1.27	0.90	1.0	0.79	1.10	0.01	0.01	0.03	0.14	0.26	0.35	0.50	0.77
Czech Republic [d]	1985–1979	0.36		0.17	0.48									
	1980–1984	0.34		0.18	0.52									
	1985–1989	0.36		0.13	0.38									
	1990–1994	0.48		0.69	1.44									
Denmark [e]	1990–1994	1.10	0.20	0.28	0.26	1.45	0.00	0.00	0.01	0.07	0.00	0.02	0.25	0.82
Finland	1975–1979		0.01	0.01		1.58								
	1980–1984		0.00	0.01		2.58								
	1985–1989		0.01	0.05		3.47					0.25			
	1990–1994	0.02	0.00	0.00	0.11	0.64	0.00	0.00	0.00	0.04	0.00	0.00	0.00	0.33
France	1975–1979	20.9	3.19	9.32	0.44	2.92	0.01							
	1980–1984	21.0	2.86	8.47	0.40	2.97	0.00							
	1985–1989	19.6	2.48	6.14	0.31	2.47	0.00							
	1990–1994	16.3	1.87	3.68	0.23	1.97	0.00	0.00	0.01	0.11				
Germany [f]	1975–1979	0.71		3.80	5.37									
	1980–1984	0.84		3.04	3.64									
	1985–1989	1.66		1.15	0.69									
Hungary [g]	1977–1979	0.12	0.01	0.01	0.06	1.49								
	1980–1984	0.13	0.01	0.00	0.03	0.83								
	1985–1989	0.12	0.01	0.01	0.07	0.96								

Table 11 (continued)

Country / area	Period	Monitored workers (thousands)	Measurably exposed workers (thousands)	Annual collective effective dose (man Sv)	Average annual effective dose (mSv)		Distribution ratio (number of workers)				Distribution ratio (collective dose)			
					Monitored workers	Measurably exposed workers	NR_{15}	NR_{10}	NR_5	NR_1	SR_{15}	SR_{10}	SR_5	SR_1
India	1980–1984	2.78	1.97	6.36	2.29	3.23	0.03				0.36			
	1985–1989	3.62	2.38	4.65	1.28	1.96	0.01				0.18			
Indonesia [h]	1975–1979	0.02		0.09	3.87		0.13				0.37			
	1980–1984	0.03	0.04	0.10	2.72	3.10	0.16				0.72			
	1985–1989	0.10	0.10	0.09	0.95	0.95	0.03				0.47			
Italy	1985–1989	2.44	0.45	0.26	0.11	0.58	0.00				0.01			
	1990–1994													
Japan [i]	1978–1979	4.12		2.13	0.52		0.00							
	1980–1984	7.01		7.97	1.14		0.02							
	1985–1989	9.18		7.72	0.84		0.01							
	1990–1994	8.15	1.04	1.53	0.19	1.48	0.00	0.00	0.01	0.05	0.01	0.10	0.38	0.83
Netherlands	1990–1994	1.65	0.40	0.12	0.07	0.27	0.00	0.00	0.00	0.01	0.00	0.04	0.06	0.31
Norway [j]	1980–1984	0.68	0.14	0.53	0.77	3.76	0.01				0.34			
	1985–1989	0.76	0.15	0.58	0.76	3.88	0.01				0.35			
	1990–1994	0.20	0.09	0.17	0.85	1.83	0.00	0.00	0.04	0.23				
Republic of Korea [k]	1975–1979	0.25		0.12	0.46		0.00							
	1980–1984	0.79	0.14	0.50	0.64	3.58	0.01							
	1985–1989	0.99	0.15	0.65	0.65	4.36	0.01							
Russian Fed.	1992–1994		6.74	16.1		2.39	0.02				0.13			
Slovenia	1990–1994	0.02	0.01	0.02	1.10	1.61	0.00	0.00	0.00	0.15	0.00	0.00	0.00	0.14
South Africa	1975–1979	0.25		0.12	0.46		0.00				0.07			
	1980–1984	0.24		0.08	0.33		0.00				0.09			
	1985–1989	0.23		0.07	0.34									
	1990–1994	0.05	0.03	0.02	0.35	0.72	0.00	0.00	0.00	0.10	0.00	0.00	0.00	0.44
Sweden	1990–1994	0.45	0.18	0.57	1.26	3.14	0.01	0.03	0.09	0.20	0.22	0.39	0.72	0.94
Thailand	1990–1994	0.03	0.01	0.01	0.47	1.26	0.00	0.00	0.01	0.11	0.00	0.00	0.11	0.63
United Kingdom	1975–1979	8.49		37.4	4.40		0.09							
	1980–1984	9.00		28.2	3.13		0.05							
	1985–1989	9.40		24.0	2.55		0.03							
	1990–1994	5.63		5.60	1.00									

Table 11 (continued)

Country / area	Period	Monitored workers (thousands)	Measurably exposed workers (thousands)	Annual collective effective dose (man Sv)	Average annual effective dose (mSv): Monitored workers	Average annual effective dose (mSv): Measurably exposed workers	Distribution ratio (number of workers): NR_{15}	NR_{10}	NR_{5}	NR_{1}	Distribution ratio (collective dose): SR_{15}	SR_{10}	SR_{5}	SR_{1}
United States	1975–1979	30.3	14.8	33.0	1.09	2.24								
	1980–1984	28.8	12.7	24.2	0.84	1.90								
	1985–1989	31.7	11.9	19.2	0.60	1.61								
	1990–1994													
Total [l m]	1975–1979	63.4		96.3	1.52		0.04				0.42			
	1980–1984	75.5		89.4	1.18		0.02				0.39			
	1985–1989	82.6		66.0	0.80		0.00				0.30			
	1990–1994	46.3	16.4	35.9	0.77	2.18	0.00	0.01	0.02	0.13	0.22	0.36	0.52	0.78
World [n]	1975–1979	120		170	1.4									
	1980–1984	130		150	1.1									
	1985–1989	130		100	0.82			0.01			0.30			
	1990–1994	120	36.0	90	0.78	2.50	0.00	0.01	0.02	0.13	0.22	0.36	0.52	0.78

a Data are annual averages over the periods indicated.
b Data are for research activities carried out by Ontario Hydro and AECL; for 1975–1987, the data contain a component arising from isotope production, which was then undertaken by AECL.
c Includes data for fuel research, a research reactor and radioisotope production.
d The data for 1985–1989 refer to Czechoslovakia.
e Data refer to work at Risø National Laboratory. Activities include research reactor operation, accelerator operation, isotope production, waste handling, research and development, and education.
f The 1975–1989 is from the Federal Republic of Germany and covers only research and prototype reactors.
g Includes only workers employed at the research reactor of the Atomic Energy Institute; some other nuclear fuel cycle research may be carried out at other research and university institutes.
h Comprises data for workers at research reactors.
i Comprises exposures of workers at test and research reactors, the nuclear ship, critical assemblies and at research facilities for nuclear fuel materials.
j Comprises only workers at the Institute of Energy Technology.
k Comprises exposures of workers at TRIGA research reactors and other fuel research facilities.
l Total of reported data. In the total of the monitored workers, the measurably exposed value for the Russian Federation is included.
m The total for measurably exposed has been increased pro rata to take account of countries reporting numbers of monitored workers, but not measurably exposed workers.
n In the absence of better data the values of NR_{15} and SR_{15} for the total reported data have been considered indicative of worldwide levels.

Table 12
Worldwide average annual exposures from the commercial nuclear fuel cycle [a]

Practice	*Monitored workers* [b] *(thousands)*	*Average annual collective effective dose (man Sv)*	*Average annual collective effective dose per unit energy generated (man Sv per GW a)*	*Average annual effective dose to monitored workers*	*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	120	0.52	10	0.41	0.76
Enrichment [e]	11	5.3	0.02	0.5	0.00	0.00
Fuel fabrication	20	36	0.59	1.8	0.012	0.38 [i]
Reactor operation	150	600	11.0	4.1	0.078 [h]	0.60 [j]
Reprocessing [g]	7.2	53	0.70	7.3	0.16	0.29 [g]
Research	120	170	1.0	1.4	0.035	0.42
Total	560	2 300	20	4.1	0.20	0.63
1980–1984						
Mining [e f]	310	1 600	5.5	5.1	0.30	0.61
Milling [e f]	23	120	0.41	5.1	0.30	0.64
Enrichment [e]	4.3	0.8	0.02	0.2	0.00	0.00
Fuel fabrication	21	21	0.21	1.0	0.002	0.11 [i]
Reactor operation	290	1 000	10.0	3.6	0.069 [h]	0.52 [j]
Reprocessing [g]	9.4	47	0.75	4.9	0.10	0.11 [g]
Research	130	150	1.0	1.1	0.021	0.39
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	120	0.44	6.3	0.18	0.43
Enrichment [e]	5.0	0.4	0.02	0.08	0.00	0.00
Fuel fabrication	28	22	0.12	0.78	0.002	0.019 [i]
Reactor operation	430	1 100	5.9	2.5	0.033 [h]	0.34 [j]
Reprocessing [g]	12	36	0.65	3.0	0.064	0.12 [g]
Research	130	100	1.0	0.82	0.011	0.30
Total	880	2 500	12	2.9	0.10	0.42
1990–1994						
Mining [e f]	69 (62)	310	1.72	4.5 (5.0)	0.10	0.32
Milling [e f]	6	20	0.11	3.3	0.00	0.01
Enrichment [e]	13	1	0.02	0.12	0.00	0.00
Fuel fabrication	21 (11)	22	0.1	1.03 (2.0)	0.01	0.11
Reactor operation	530 (300)	900	3.9	1.4 (2.7)	0.00 [h]	0.08
Reprocessing [g k]	45 (24)	67	3.0	1.5 (2.8)	0.00	0.13
Research	120 (36)	90	1.0	0.78 (2.5)	0.01	0.22
Total	800 (450)	1 400	9.8	1.75 (3.1)	0.01	0.11

a The data are annual values averaged over the indicated periods.
b Data in parentheses relate to data for measurably exposed workers.
c The values of the distribution ratios should only be considered indicative of worldwide levels as they are based, in general, on data from far fewer countries than the data for number of workers and collective doses.
d This ratio applies to monitored workers.
e Also include 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^{-1} for exposure to radon daughters (10 mSv WLM^{-1} 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 revised data is not linear because exposure occurs from other than just inhalation of radon progeny. For 1990–1994 a conversion factor of 5.0 mSv WLM^{-1} for exposure to radon daughters has been used.
g Also includes the reprocessing of some fuel from the defence nuclear fuel cycle.
h Does not include data for LWGRs, FBRs and HTGRs.
i 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.
j Does not include data for GCRs, LWGRs, FBRs and HTGRs.
k In the absence of sufficient data on equivalent electrical energy generated from reporting countries for 1990-1994, the Committee has taken the normalized average annual collective effective per unit energy generated to be the same as that for the previous period.

Table 13
Exposures to workers from medical uses of radiation [a]
Data from UNSCEAR Survey of Occupational Exposures

Country / area	Period	Monitored workers (thousands)	Measurably exposed workers (thousands)	Annual collective effective dose (man Sv)	Average annual effective dose (mSv)		Distribution ratio [b] (number of workers)				Distribution ratio (collective dose)			
					Monitored workers	Measurably exposed workers	NR_{15}	NR_{10}	NR_5	NR_1	SR_{15}	SR_{10}	SR_5	SR_1
Diagnostic radiology														
Argentina	1985–1989	2.20	0.83	2.89	1.31	3.46	0.02				0.56			
	1994	5.99	2.28	9.00	1.50	3.96	0.04	0.04	0.05	0.17	0.61	0.63	0.69	0.93
Australia [c d]	1975–1979	3.22		1.70	0.53									
	1985–1989	6.21	4.42	0.37	0.059	0.08								
	1990–1994	8.19	5.52	1.04	0.13	0.19	0.00	0.00	0.00	0.01	0.20	0.22	0.27	0.43
Brazil [e]	1985–1989	3.93	1.01	2.99	0.76	2.97	0.01				0.34			
	1990–1994	4.29	0.50	1.40	0.33	2.58	0.00	0.01	0.01	0.05	0.35	0.46	0.63	0.91
Bulgaria	1990–1994	2.96	0.30	0.97	0.33	1.51	0.00	0.00	0.00	0.05	0.01	0.02	0.06	0.25
Canada	1975–1979	8.4	4.5	3.23	0.38	0.72	0.00				0.07			
	1980–1984	9.5	2.0	1.71	0.18	0.87	0.00				0.04			
	1985–1989	10.7	2.7	1.75	0.16	0.64	0.00				0.03			
	1990–1994	13.2	2.52	1.35	0.10	0.53	0.00	0.00	0.00	0.02	0.05	0.06	0.11	0.47
China	1985–1989	78.1	13.3	143	1.84	10.8	0.03				0.45			
	1990–1994	12.5	11.7	21.2	1.70	1.80	0.01	0.03	0.05	0.31	0.25	0.34	0.44	0.78
China, Taiwan Province [f]	1985–1989	3.4		1.49	0.44									
	1990–1994	5.10	0.99	0.74	0.15	0.75								
Croatia	1990–1994	2.90	1.80	0.50	0.17	0.28								
Cyprus	1990–1994	0.15	0.01	0.15	1.00	1.50	0.01	0.01	0.03	0.28	0.21	0.26	0.38	0.93
Czech Republic [g]	1975–1979	5.08	1.27	3.16	0.62	2.50	0.00				0.18			
	1980–1984	6.89	2.22	4.48	0.65	2.02	0.00				0.10			
	1985–1989	8.56	2.66	5.84	0.68	2.21	0.00				0.13			
	1990–1994	7.71	3.66	6.04	0.78	1.65	0.00	0.00	0.01	0.16	0.06	0.10	0.18	0.71
Denmark [h]	1975–1979	4.28		1.01	0.24		0.00							
	1980–1984	4.02		0.64	0.16		0.00				0.02			
	1985–1989	3.82		0.43	0.11		0.00				0.01			
	1990–1994	3.72	1.17	0.48	0.13	0.41	0.00	0.00	0.00	0.02	0.00	0.01	0.07	0.40
Ecuador [h]	1993–1994	0.66	0.41	0.50	0.77	1.24	0.00	0.01	0.01	0.32				

Table 13 (continued)

Country / area	Period	Monitored workers (thousands)	Measurably exposed workers (thousands)	Annual collective effective dose (man Sv)	Average annual effective dose (mSv)		Distribution ratio [b] (number of workers)				Distribution ratio (collective dose)			
					Monitored workers	Measurably exposed workers	NR_{15}	NR_{10}	NR_5	NR_1	SR_{15}	SR_{10}	SR_5	SR_1
Finland [i j]	1975–1979	3.88	0.08	0.58	0.15	6.93	0.00				0.46			
	1980–1984	4.37	0.29	0.71	0.16	2.43	0.00				0.15			
	1985–1989	4.82	0.30	0.92	0.19	3.10	0.00				0.28			
	1990–1994	4.71	0.43	1.14	0.24	2.63	0.00	0.00	0.01	0.05	0.27	0.40	0.58	0.91
France [k]	1975–1979	33.4		39.7	1.19		0.00							
	1980–1984	49.0	6.05	28.3	0.58	4.67	0.00							
	1985–1989	61.8	6.35	20.3	0.33	3.19	0.00							
Gabon	1990–1994	0.01		0.00	0.02		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Germany [l]	1980–1984	19.2	3.12	2.05	0.11	0.66					0.08			
	1985–1989	20.4	1.17	1.68	0.09	1.44					0.11			
Greece	1990–1994	4.07	0.97	3.74	0.92	3.86	0.01	0.02	0.04	0.13	0.44	0.55	0.72	0.94
Hungary	1975–1979	5.96	1.22	2.32	0.39	1.90	0.00				0.11			
	1980–1984	7.49	1.01	1.61	0.22	1.60	0.00				0.09			
	1985–1989	7.26	0.98	1.49	0.21	1.53	0.00				0.08			
	1990–1994	6.76	0.65	0.71	0.10	1.09	0.00	0.00	0.00	0.03	0.04	0.06	0.17	0.67
Iceland [h j]	1990–1994	0.44	0.13	0.12	0.26	0.48	0.00	0.00	0.01	0.06	0.13	0.26	0.35	0.69
India	1975–1979	6.50	3.64	3.75	0.58	1.03	0.00				0.21			
	1980–1984	8.00	3.97	2.76	0.35	0.70	0.00				0.15			
	1985–1989	10.4	5.42	3.54	0.34	0.65	0.00				0.14			
	1990–1994	10.7	5.59	2.58	0.24	0.42	0.00	0.00	0.01	0.05	0.12	0.18	0.30	0.68
Indonesia	1975–1979	0.98	0.94	1.59	1.62	1.70	0.00				0.02			
	1980–1984	1.84	1.76	2.94	1.60	1.68	0.00				0.00			
	1985–1989	2.30	2.19	3.84	1.67	1.75	0.00				0.02			
Ireland	1985–1989	1.46	0.12	0.55	0.38	4.69								
	1991–1994	1.43	0.15	0.09	0.06	0.60	0.00	0.00	0.00	0.01	0.00	0.03	0.11	0.48
Kuwait	1992–1994	0.48	0.09	0.17	0.36	1.56	0.00	0.00	0.00	0.01	0.18	0.21	0.30	0.60
Myanmar	1990–1994	0.03	0.03	0.02	0.62	0.63	0.00	0.00	0.00	0.04				
Netherlands	1990–1994	9.82	4.24	7.01	0.71	1.64	0.01	0.02	0.03	0.10	0.34	0.47	0.64	0.87
Norway [m]	1990–1992	2.92	0.98	2.29	0.78	2.32	0.01	0.01	0.04	0.14				
Pakistan	1990–1994	0.64	0.62	2.30	3.60	3.99	0.07	0.09	0.15	0.40	0.60	.068	0.79	0.93

Table 13 (continued)

Country / area	Period	Monitored workers (thousands)	Measurably exposed workers (thousands)	Annual collective effective dose (man Sv)	Average annual effective dose (mSv)		Distribution ratio [b] (number of workers)				Distribution ratio (collective dose)			
					Monitored workers	Measurably exposed workers	NR_{15}	NR_{10}	NR_5	NR_1	SR_{15}	SR_{10}	SR_5	SR_1
Peru	1980–1989 1985–1989 1994	1.37 1.48 1.90	 1.59	4.95 5.10 4.94	3.61 3.45 2.60	 3.10	 0.06	 0.09	 0.13	 0.42				
Slovakia	1990–1994	3.39	0.52	0.97	0.28	1.87	0.00	0.00	0.01	0.07	0.13	0.20	0.37	
Slovenia	1993–1994	1.58	1.23	0.61	0.38	0.49	0.00	0.00	0.00	0.06	0.02	0.02	0.08	0.33
Spain	1985–1989 1990–1994	34.3	30.9	25.9	0.76	0.84	0.00				0.12			
Sri Lanka	1990–1994	0.24	0.07	0.12	0.50	1.62	0.00	0.00	0.01	0.07	0.20	0.22	0.32	0.68
Syrian Arab Republic	1990–1994	0.80	0.07	2.42	3.03	4.4	0.00	0.00	0.00	0.01	0.00	0.00	0.01	0.12
Thailand	1990–1994	3.80	1.27	0.73	0.19	0.58	0.00	0.00	0.01	0.04	0.12	0.21	0.35	0.72
United Kingdom [n]	1991	13.7		1.40	0.10									
United Rep. of Tanzania	1990–1994	0.41	0.41	1.90	4.62	4.74	0.02	0.15	0.49	0.85	0.05	0.40	0.81	0.98
Total reported data [o p]	1975–1979 1980–1984 1985–1989 1990–1994	65.7 104 213 135	 54.9	54.8 48.3 194 76.7	0.84 0.47 0.91 0.57	 1.40	0.00 0.00 0.02 0.01	 0.01	 0.02	 0.10	0.14 0.08 0.40 0.27	 0.35	 0.46	 0.75
World [q]	1975–1979 1980–1984 1985–1989 1990–1994	630 1060 1350 950 (840)	 350 (330)	600 720 760 470 (485)	0.94 0.68 0.56 0.50 (0.57)	 1.34 (1.47)	0.00 0.00 0.00 0.00 (0.00)	 0.01 (0.01)	 0.02 (0.02)	 0.09 (0.10)	0.11 0.10 0.22 0.19 (0.19)	 0.30 (0.29)	 0.44 (0.43)	 0.77 (0.76)
Dental radiology														
Argentina	1985–1989	0.07	0.04	0.03	0.46	0.74	0.01				0.42			
Australia [c d]	1975–1979 1985–1989 1990–1994	1.16 3.80 3.88	 1.60 1.58	 0.02 0.08	 0.00 0.02	 0.01 0.05	 0.00	 0.00	 0.00	 0.00	 0.24	 0.24	 0.31	 0.41
Brazil [e]	1990–1994	0.72	0.02	0.11	0.15	5.05	0.00	0.00	0.01	0.02	0.61	0.70	0.79	0.96
Bulgaria	1992	0.20	0	0.04	0.21		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Table 13 (continued)

Country / area	Period	Monitored workers (thousands)	Measurably exposed workers (thousands)	Annual collective effective dose (man Sv)	Average annual effective dose (mSv)		Distribution ratio [b] (number of workers)				Distribution ratio (collective dose)			
					Monitored workers	Measurably exposed workers	NR_{15}	NR_{10}	NR_5	NR_1	SR_{15}	SR_{10}	SR_5	SR_1
Canada	1975–1979	13.1	0.97	0.42	0.03	0.44	0.00				0.11			
	1980–1989	19.5	0.94	0.60	0.31	0.64	0.00				0.13			
	1985–1989	24.4	0.94	0.64	0.03	0.68	0.00				0.28			
	1990–1994	26.8	0.20	0.25	0.01	1.24	0.00	0.00	0.00	0.00	0.54	0.62	0.65	0.77
Croatia	1990–1994	0.45	0.03	0.05	0.10	1.67								
Cyprus	1990–1994	0.02	0.01	0.01	0.47	0.94	0.01	0.01	0.01	0.11	0.44	0.44	0.44	0.79
Ecuador [h]	1993–1994	0.08	0.05	0.05	0.66	0.93	0.00	0.00	0.01	0.26				
Finland	1990–1994	0.18	0	0.00	0		0.00	0.00	0.00	0.00				
France [k]	1975–1979	6.17		2.61	0.42		0.00							
	1980–1984	11.2	0.74	2.42	0.22	3.25	0.00							
	1985–1989	16.7	0.86	1.97	0.12	2.31	0.00							
Germany [l r]	1985–1989	7.82	0.18	0.39	0.05	2.16	0.00				0.60			
	1990–1994	6.73	0.15	0.21	0.03	1.39	0.00	0.00	0.00	0.00	0.44	0.55	0.58	0.77
Greece	1990–1994	0.03	0.00	0.01	0.20	5.32	0.01	0.01	0.01	0.02	0.63	0.63	0.91	0.94
Hungary	1975–1979	0.24	0.01	0.01	0.06	1.54								
	1980–1984	0.32	0.01	0.01	0.03	1.02								
	1985–1989	0.24	0.00	0.00	0.01	0.90								
Iceland	1990–1994	0.04	0	0	0	0.10	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
India	1975–1979	0.37	0.21	0.17	0.45	0.80	0.00				0.04			
	1980–1984	0.45	0.21	0.17	0.38	0.80	0.00				0.06			
	1985–1989	0.63	0.32	0.24	0.38	0.74	0.00				0.19			
	1990–1994	0.73	0.31	0.11	0.15	0.36	0.00	0.00	0.00	0.03	0.03	0.05	0.15	0.55
Indonesia	1975–1979	0.02	0.02	0.03	1.31	1.31								
	1980–1984	0.15	0.15	0.28	1.84	1.84								
	1985–1989	0.10	0.10	0.15	1.50	1.50	0.00				0.02			
Ireland	1985–1989	0.13	0.00	0.00	0.01	0.30								
	1990–1994	0.97	0.00	0.01	0.00	2.75	0.00	0.00	0.00	0.00	0.00	0.00	0.45	0.55
Italy	1985–1989	1.01	0.39	0.07	0.07	0.19	0.00				0.28			

Table 13 (continued)

Country / area	Period	Monitored workers (thousands)	Measurably exposed workers (thousands)	Annual collective effective dose (man Sv)	Average annual effective dose (mSv)		Distribution ratio [b] (number of workers)				Distribution ratio (collective dose)			
					Monitored workers	Measurably exposed workers	NR_{15}	NR_{10}	NR_5	NR_1	SR_{15}	SR_{10}	SR_5	SR_1
Japan	1975–1979	0.35	0.08	0.13	0.36	1.68								
	1980–1984	1.75	0.20	0.34	0.20	1.69								
	1985–1989	3.53	0.35	0.56	0.16	1.60								
	1990–1994	5.40	0.45	0.57	0.11	1.29	0.00	0.00	0.00	0.03	0.22	0.29	0.40	0.82
Kuwait	1992–1994	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Myanmar	1990–1994	0.00	0.00	0.00	0.75	0.75	0.00	0.00	0.00	0.53				
Netherlands	1990–1994	3.33	0.42	0.13	0.04	0.27	0.00	0.00	0.00	0.00	0.27	0.32	0.39	0.45
Norway	1990–1992	0.07	0.00	0.00	0.01	0.28	0.00	0.00	0.00	0.00				
Pakistan	1994	0.00	0.00	0.00	0.27	2.67	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Slovakia	1990–1994	0.01	0.00	0.00	0.08	0.75	0.00	0.00	0.00	0.03	0.00	0.00	0.00	0.67
Slovenia	1993–1994	0.23	0.14	0.05	0.20	0.34	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.09
South Africa	1975–1979	2.27	1.06	0.12	0.05	0.11								
	1980–1984	2.82	0.53	1.52	0.54	2.88	0.00				0.64			
	1985–1989	3.33	0.37	4.49	1.35	12.2	0.00				0.18			
Spain	1985–1989	1.29	1.21	1.56	1.21	1.30	0.01				0.10			
	1990–1994													
Sweden	1992–1994	0.29		0.01	0.04									
Switzerland [s]	1975–1979	7.09		1.21	0.17		0.00				0.07			
	1980–1984	9.13		0.96	0.11		0.00				0.89			
	1985–1989	10.7		0.26	0.03		0.00				0.02			
	1990–1994	11.0		0.25	0.02		0.00	0.00	0.00	0.00	0.16	0.16	0.20	0.38
Thailand	1990–1994	0.27	0.06	0.03	0.12	0.35	0.00	0.00	0.00	0.01	0.16	0.28	0.28	0.71
United Kingdom [n]	1980–1984	20		2	0.1									
	1985–1989	20		2	0.1									
	1991	20		2	0.1									
United States [t]	1975–1979	215		80	0.37									
	1980–1984	259		60	0.23									
	1985–1989	307	61	12	0.04	0.20								

Table 13 (continued)

Country / area	Period	Monitored workers (thousands)	Measurably exposed workers (thousands)	Annual collective effective dose (man Sv)	Average annual effective dose (mSv)		Distribution ratio [b] (number of workers)				Distribution ratio (collective dose)			
					Monitored workers	Measurably exposed workers	NR_{15}	NR_{10}	NR_5	NR_1	SR_{15}	SR_{10}	SR_5	SR_1
Total of reported data [o p]	1975–1979	242		84.5	0.35		0.00				0.08			
	1980–1984	322		68.8	0.21		0.00				0.08			
	1985–1989	391		18.5	0.05		0.00				0.12			
	1990–1994	81.4	5.31	3.97	0.05	0.75	0.00	0.00	0.00	0.00	0.28	0.33	0.40	0.64
World [q]	1975–1979	370		120	0.32									
	1980–1984	500		93	0.20									
	1985–1989	480		25	0.05									
	1990–1994	265	17.0	16	0.06	0.89	0.00	0.00	0.00	0.01	0.24	0.29	0.33	0.56
		(200)	(17)	(13)	(0.04)	(0.77)	(0.00)	(0.00)	(0.00)	(0.01)	(0.20)	(0.24)	(0.28)	(0.48)
Nuclear medicine														
Argentina	1985–1989	0.92	0.25	0.76	0.82	3.08	0.01				0.26			
	1990–1994	0.42	0.23	1.14	2.71	4.91	0.05	0.05	0.08	0.34	0.57	0.59	0.67	0.96
Australia [c d]	1975–1979	0.67		0.20	0.30									
	1985–1989	2.72	1.31	0.44	0.16	0.33								
	1990–1994	1.58	0.86	0.64	0.41	0.75	0.00	0.00	0.01	0.14	0.01	0.01	0.09	0.76
Brazil [e]	1985–1989	0.92	0.25	0.76	0.82	3.08	0.01				0.26			
	1990–1994	0.43	0.19	0.67	1.57	3.50	0.02	0.04	0.08	0.24	0.35	0.49	0.71	0.94
Bulgaria	1990–1994	0.19		0.20	1.03									
Canada	1975–1979	0.57	0.41	1.08	1.90	2.63	0.01				0.13			
	1980–1984	0.85	0.55	1.53	1.81	2.80	0.00				0.05			
	1985–1989	1.14	0.83	2.24	1.96	2.71	0.00				0.04			
	1990–1994	1.42	1.00	1.95	1.37	1.96	0.00	0.00	0.04	0.46	0.01	0.03	0.21	0.91
China	1985–1989	6.08	0.71	9.52	1.57	13.3	0.01				0.27			
China, Taiwan Province	1985–1989	0.38		0.10	0.27									
	1990–1994	0.50	0.23	0.14	0.29	0.63	0.00	0.00	0.00	0.07	0.07	0.10	0.50	0.96
Croatia	1990–1994	0.06	0.04	0.05	0.80	1.10								
Cuba	1990–1994	0.17	0.17	0.46	2.79	2.79	0.01	0.13	0.27	0.83	0.12	0.21	0.36	0.95
Cyprus	1990–1994	0.01	0.01	0.01	0.67	0.73	0.00	0.00	0.00	0.22	0.00	0.00	0.00	0.59
Czech Republic [g]	1975–1979	0.74	0.22	0.43	0.58	1.83	0.00				0.04			
	1980–1984	1.08	0.67	0.99	0.92	1.48	0.00				0.03			
	1985–1989	1.46	0.75	1.26	0.87	1.68	0.00				0.01			
	1990–1994	0.76	0.70	0.74	0.98	1.05	0.00	0.00	0.01	0.35	0.01	0.04	0.10	0.68

Table 13 (continued)

Country / area	Period	Monitored workers (thousands)	Measurably exposed workers (thousands)	Annual collective effective dose (man Sv)	Average annual effective dose (mSv)		Distribution ratio [b] (number of workers)				Distribution ratio (collective dose)			
					Monitored workers	Measurably exposed workers	NR_{15}	NR_{10}	NR_5	NR_1	SR_{15}	SR_{10}	SR_5	SR_1
Denmark	1975–1979	0.45		0.34	0.76									
	1980–1984	0.48		0.30	0.62		0.00				0.03			
	1985–1989	0.50		0.35	0.70									
	1990–1994	0.53	0.35	0.41	0.78	1.18	0.00	0.00	0.01	0.31	0.02	0.03	0.09	0.83
Ecuador	1993–1994	0.03	0.02	0.04	1.48	2.00	0.00	0.02	0.09	0.54	0.00	0.00	0.00	0.00
Finland	1975–1979	0.60	0.02	0.07	0.12	4.11	0.00				0.04			
	1980–1984	0.68	0.08	0.15	0.23	1.93	0.00				0.07			
	1985–1989	0.75	0.11	0.17	0.23	1.62								
	1990–1994	677	0.13	0.15	0.22	1.15	0.00	0.00	0.00	0.09	0.00	0.00	0.06	0.76
France	1975–1979	2.76		3.25	1.18		0.00							
	1980–1984	3.37	0.62	1.61	0.48	2.60	0.00							
	1985–1989	3.21	0.54	1.03	0.32	1.92	0.00							
	1990–1994													
Germany [l]	1980–1984	0.81	0.20	0.54	0.67	2.68								
	1985–1989	0.83	0.15	0.43	0.51	2.84					0.02			
Greece	1990–1994	0.41	0.13	0.31	0.75	2.27	0.00	0.01	0.03	0.15	0.26	0.31	0.53	0.88
Hungary	1975–1979	0.36	0.03	0.05	0.14	1.66	0.00	0.09						
	1980–1984	0.54	0.09	0.18	0.33	1.93	0.00	0.14						
	1985–1989	0.72	0.14	0.22	0.31	1.62	0.00	0.01			0.01			
	1990–1994	0.76	0.15	0.20	0.27	1.40	0.00	0.00	0.01	0.08	0.02	0.05	0.20	0.78
Iceland	1990–1994	0.01	0.01	0.01	1.30	2.33	0.00	0.00	0.00	0.47	0.00	0.00	0.00	0.88
India	1975–1979	0.41	0.12	0.22	0.54	1.82	0.00				0.21			
	1980–1984	0.49	0.22	0.39	0.80	1.82	0.00				0.10			
	1985–1989	0.61	0.30	0.52	0.85	1.75	0.01				0.12			
	1990–1994	0.84	0.40	0.54	0.65	1.36	0.00	0.01	0.03	0.15	0.06	0.16	0.40	0.82
Indonesia	1980–1984	0.01	0.01	0.01	1.23	1.23								
	1985–1989	0.1	0.01	0.02	1.20	1.20								
Ireland	1985–1989		0.02	0.01		0.50								
	1991–1994	0.18	0.02	0.01	0.06	0.45	0.00	0.00	0.00	0.02	0.00	0.00	0.31	0.76
Jordan	1990–1994	0.47	0.42	0.57	1.23	1.36	0.01	0.02	0.05	0.19	0.20	0.32	0.45	0.72
Kuwait	1992–1994	0.06	0.02	0.02	0.37	0.97	0.00	0.00	0.00	0.11	0.00	0.00	0.00	0.57

Table 13 (continued)

Country / area	Period	Monitored workers (thousands)	Measurably exposed workers (thousands)	Annual collective effective dose (man Sv)	Average annual effective dose (mSv)		Distribution ratio [b] (number of workers)				Distribution ratio (collective dose)			
					Monitored workers	Measurably exposed workers	NR_{15}	NR_{10}	NR_5	NR_1	SR_{15}	SR_{10}	SR_5	SR_1
Mexico [u]	1985–1989 1990–1994	0.42 0.60	 0.26	1.21 0.73	2.88 1.21	 4.63	 0.03				 0.33			
Myanmar	1990–1994	0.02	0.02	0.02	1.26	1.26	0.03	0.03	0.09	0.50				
Netherlands	1990–1994	0.57	0.35	0.26	0.45	0.73	0.00	0.00	0.01	0.13	0.03	0.06	0.14	0.57
Norway	1990–1992	0.24	0.10	0.14	0.59	1.47	0.00	0.00	0.02	0.19				
Pakistan	1990–1994	0.23	0.22	2.07	8.90	12.6	0.26	0.38	0.55	0.81	0.72	0.82	0.94	1.00
Peru	1980–1984 1985–1989 1994	0.12 0.13 0.03	 0.03	0.43 0.35 0.15	3.73 2.75 5.00	 5.00	 0.00	 0.00	 0.30	 0.80				
Slovakia	1990–1994	0.30	0.21	0.27	0.93	1.30	0.00	0.00	0.01	0.36	0.04	0.04	0.09	0.78
Slovenia	1993–1994	0.34	0.34	0.17	0.49	0.49	0.00	0.00	0.00	0.08	0.00	0.00	0.02	0.28
Spain	1985–1989	0.92	0.83	1.61	1.74	1.93	0.01				0.11			
Sri Lanka	1990–1994	0.03	0.01	0.00	0.19	0.48	0.00	0.00	0.00	0.03	0.00	0.00	0.00	0.37
Syrian Arab Republic	1990–1994	0.06	0.01	0.03	0.48	3.16	0.00	0.00	0.01	.004	0.00	0.00	0.15	0.31
Thailand	1990–1994	0.22	0.08	0.23	1.04	2.89	0.01	0.01	0.04	0.17	0.44	0.48	0.69	0.92
United Kingdom [n]	1991	1.40		0.30	0.22									
Total reported data [o p]	1975–1979 1980–1984 1985–1989 1990–1994	5.66 7.91 15.9 13.5	 7.63	5.21 5.72 16.6 12.8	0.92 0.72 1.04 0.95	 1.68	0.00 0.00 0.01 0.01	 0.02	 0.04	 0.24	0.11 0.05 0.17 0.24	 0.29	 0.42	 0.81
World [q]	1975–1979 1980–1984 1985–1989 1990–1994	61 81 90 115 (100)	 65 (60)	62 85 85 90 (86)	1.01 1.04 0.95 0.79 (0.86)	 1.41 (1.40)	0.00 0.00 0.00 0.00 (0.00)	 0.01 (0.01)	 0.02 (0.03)	 0.21 (0.21)	0.09 0.03 0.10 0.10 (0.15)	 0.15 (0.20)	 0.27 (0.31)	 0.74 (0.74)
Radiotherapy														
Argentina	1985–1989 1990–1994	0.27 0.40	0.08 0.10	0.28 0.25	1.04 0.64	3.61 2.61	0.00 0.01	 0.01	 0.02	 0.10	0.10 0.30	 0.43	 0.51	 0.89

Table 13 (continued)

Country / area	Period	Monitored workers (thousands)	Measurably exposed workers (thousands)	Annual collective effective dose (man Sv)	Average annual effective dose (mSv)		Distribution ratio [b] (number of workers)				Distribution ratio (collective dose)			
					Monitored workers	Measurably exposed workers	NR_{15}	NR_{10}	NR_5	NR_1	SR_{15}	SR_{10}	SR_5	SR_1
Australia [c d]	1975–1979	0.64		1.47	2.30									
	1985–1989	0.78	0.63	0.27	0.34	0.42	0.00				0.17			
	1990–1994	1.08	0.71	0.25	0.23	0.35	0.00	0.00	0.00	0.03	0.17	0.21	0.26	0.46
Brazil [e]	1985–1989	0.72	0.24	0.90	1.24	3.73	0.02				0.44			
	1990–1994	0.80	0.30	1.17	1.47	3.95	0.01	0.02	0.05	0.17	0.57	0.64	0.76	0.94
Bulgaria	1990–1994	0.33		0.48	1.44									
Canada	1975–1979	0.54	0.35	0.75	1.40	2.14	0.01				0.27			
	1980–1984	0.62	0.36	0.63	1.01	1.78	0.00				0.08			
	1985–1989	0.72	0.43	0.59	0.82	1.38	0.00				0.05			
	1990–1994	1.03	0.44	0.35	0.34	0.80	0.00	0.00	0.01	0.09	0.07	0.09	0.17	0.61
China	1985–1989	2.54	0.35	3.54	1.39	10.0	0.02				0.31			
	1990–1994	1.46	1.40	1.68	1.15	1.20	0.01	0.01	0.03	0.39	0.12	0.17	0.28	0.67
China, Taiwan Province	1985–1989	0.36		0.06	0.16									
	1990–1994	0.42	0.14	0.05	0.13	0.36	0.00	0.00	0.00	0.01	0.09	0.09	0.14	0.29
Croatia	1990–1994	0.03	0.03	0.02	0.70	0.90								
Cuba	1990–1994	0.18	0.18	0.39	2.18	2.19	0.01	0.02	0.06	0.68	.0.14	0.20	0.32	0.92
Cyprus	1990–1994	0.01	0.01	0.01	0.85	0.96	0.00	0.00	0.00	0.36	0.00	0.00	0.00	0.67
Czech Republic [e g]	1975–1979	0.76	0.38	1.43	1.89	3.82	0.00				0.05			
	1980–1989	1.11	0.69	2.08	1.87	3.01	0.01				0.08			
	1985–1989	1.29	0.63	1.83	1.42	2.90	0.00				0.10			
	1990–1994	0.94	0.81	1.04	1.10	1.28	0.00	0.00	0.01	0.35	0.01	0.03	0.06	0.61
Denmark	1975–1979	0.92		1.95	2.12		0.03				0.37			
	1980–1984	1.01		1.12	1.11		0.01				0.17			
	1985–1989	1.01		0.38	0.38		0.00				0.02			
	1990–1994	1.03	0.24	0.15	0.15	0.64	0.00	0.00	0.00	0.04	0.00	0.03	0.14	0.62
Ecuador	1993–1994	0.06	0.05	0.07	1.06	1.44	0.01	0.02	0.04	0.35				
Finland	1980–1984	0.25	0.03	0.05	0.22	2.08	0.00				0.30			
	1985–1989	0.24	0.02	0.03	0.10	1.44	0.00				0.25			
	1990–1994	0.28	0.02	0.01	0.05	0.65	0.00	0.00	0.00	0.01	0.00	0.00	0.10	0.43

Table 13 (continued)

Country / area	Period	Monitored workers (thousands)	Measurably exposed workers (thousands)	Annual collective effective dose (man Sv)	Average annual effective dose (mSv)		Distribution ratio [b] (number of workers)				Distribution ratio (collective dose)			
					Monitored workers	Measurably exposed workers	NR_{15}	NR_{10}	NR_5	NR_1	SR_{15}	SR_{10}	SR_5	SR_1
France [m]	1975–1979	4.77		8.77	1.84		0.01							
	1980–1984	6.01	1.30	6.08	1.01	4.68	0.01							
	1985–1989	6.49	1.23	3.97	0.61	3.22	0.01							
	1990–1994													
Germany [l]	1980–1984	1.20	0.31	1.09	0.91	3.57					0.24			
	1985–1989	1.03	0.17	0.68	0.66	4.00					0.23			
Greece	1990–1994	0.22	0.01	0.03	0.11	2.00	0.00	0.00	0.01	0.03	0.00	0.19	0.51	0.88
Hungary	1975–1979	0.36	0.14	0.73	2.05	5.15	0.03				0.36			
	1980–1984	0.45	0.14	0.61	1.36	4.31	0.02				0.24			
	1985–1989	0.55	0.15	0.61	1.10	3.97	0.01				0.23			
	1990–1994	0.47	0.10	0.33	0.70	3.28	0.01	0.02	0.04	0.14	0.28	0.36	0.59	0.94
Iceland	1990–1994	0.04	0.01	0.01	0.18	0.60	0.00	0.00	0.00	0.02	0.00	0.00	0.00	0.83
India	1975–1979	2.49	1.43	3.91	1.57	2.73	0.02				0.39			
	1980–1984	2.98	1.53	3.39	1.14	2.22	0.01				0.30			
	1985–1989	4.17	2.28	3.94	0.95	1.73	0.01				0.23			
	1990–1994	4.52	2.35	3.15	0.70	1.34	0.00	0.01	0.03	0.15	0.17	0.26	0.43	0.81
Indonesia	1975–1979	0.09	0.09	0.19	2.10	2.20								
	1980–1984	0.31	0.30	0.50	1.60	1.68	0.00				0.02			
	1985–1989	0.23	0.22	0.35	1.55	1.63	0.00				0.04			
Ireland	1985–1989	0.30	0.14	0.15	0.50	1.05								
	1991–1994	0.28	0.07	0.03	0.12	0.43	0.00	0.00	0.00	0.03	0.00	0.00	0.04	0.58
Jordan	1990–1994	0.02	0.02	0.02	1.03	1.03	0.00	0.00	0.00	0.44	0.00	0.00	0.00	0.57
Kuwait	1992–1994	0.06	0.00	0.01	0.17	1.35	0.00	0.00	0.00	0.03	0.00	0.00	0.00	0.33
Mexico [u]	1985–1989	0.31	0.26	0.88	2.84	3.41	0.03				0.33			
	1990–1994	0.66		0.45	0.68									
Myanmar	1990–1994	0.02	0.02	0.01	0.58	0.58	0.00	0.00	0.00	0.14				
Netherlands	1990–1994	1.55	0.49	0.38	0.25	0.77	0.00	0.00	0.00	0.02	0.49	0.52	0.56	0.76
Pakistan	1990–1994	0.13	0.12	1.35	10.5	11.6	0.32	0.45	0.64	0.86	0.68	0.82	0.94	1.00
Peru	1980–1984	0.09		0.54	6.18									
	1985–1989	0.09		0.48	5.17									
	1994	0.05	0.05	0.24	5.00	5.00	0.00	0.08	0.42	0.88				

Table 13 (continued)

Country / area	*Period*	*Monitored workers (thousands)*	*Measurably exposed workers (thousands)*	*Annual collective effective dose (man Sv)*	*Average annual effective dose (mSv)*		*Distribution ratio* [b] *(number of workers)*				*Distribution ratio (collective dose)*			
					Monitored workers	*Measurably exposed workers*	NR_{15}	NR_{10}	NR_5	NR_1	SR_{15}	SR_{10}	SR_5	SR_1
Slovak Republic	1990–1994	0.30	0.17	0.26	0.88	1.50	0.00	0.01	0.02	0.23	0.03	0.11	0.21	0.75
Slovenia	1993–1994	0.07	0.50	0.01	0.08	0.13	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Spain	1985–1989	1.01	0.96	0.88	0.86	0.91	0.00				0.02			
Sri Lanka	1990–1994	0.10	0.04	0.06	0.63	1.56	0.01	0.01	0.02	0.06	0.37	0.45	0.52	0.64
Syrian Arab Republic	1990–1994	0.04	0.01	0.01	0.29	1.37	0.00	0.00	0.00	0.04	0.00	0.00	0.12	0.48
Thailand	1990–1994	0.55	0.04	0.04	0.08	1.05	0.00	0.00	0.00	0.01	0.26	0.32	0.47	0.76
United Kingdom [n]	1991	2.68		0.40	0.15									
United Rep. of Tanzania	1990–1994	0.02	0.02	0.24	10.43	10.43	0.06	0.39	0.79	1.00	0.10	0.57	0.91	1.00
Total reported data [o p]	1975–1979	9.31		16.5	1.78		0.12				0.30			
	1980–1984	13.3		15.3	1.15		0.01				0.20			
	1985–1989	18.8		16.6	0.88		0.01				0.21			
	1990–1994	19.8	9.41	13.0	0.65	1.38	0.00	0.01	0.03	0.15	0.25	0.34	0.46	0.79
World [q]	1975–1979	84		190	2.23									
	1980–1984	110		180	1.58									
	1985–1989	110		100	0.87									
	1990–1994	120	48	65	0.55	1.33	0.00	0.01	0.02	0.13	0.15	0.25	0.37	0.74
		(105)	(52)	(72)	(0.68)	(1.39)	(0.00)	(0.01)	(0.02)	(0.16)	(0.17)	(0.27)	(0.39)	(0.76)
All other medical uses [v]														
Australia	1991–1994	0.05	0.01	0.00	0.06	0.58	0.00	0.00	0.00	0.02	0.00	0.00	0.00	0.70
Brazil [e]	1990–1994	0.16	0.01	0.02	0.11	1.68	0.00	0.00	0.01	0.02	0.00	0.28	0.49	0.85
Bulgaria	1990–1994	0.25	0.02	0.06	0.26		0.00	0.00	0.00	0.02				
Canada	1990–1994	21.3	2.66	1.75	0.08	0.66	0.00	0.00	0.00	0.02	0.08	0.12	0.22	0.57
Czech Republic [g]	1975–1979	6.78	1.89	5.16	0.76	2.73	0.00				0.13			
	1980–1984	9.38	3.62	7.80	0.83	2.15	0.00				0.08			
	1985–1989	11.6	4.04	9.12	0.78	2.25	0.00				0.10			
Cuba	1991–1994	0.11	0.11	0.14	1.20	1.21	0.00	0.00	0.02	0.59	0.00	0.02	0.10	0.81
Cyprus	1990–1994	0.09	0.04	0.03	0.29	0.75	0.00	0.00	0.00	0.11	0.00	0.00	0.05	0.66
Ecuador	1993–1994	0.03	0.03	0.04	1.10	1.10	0.00	0.00	0.00	0.49				
Germany [w]	1990–1994	223	25.0	23.7	0.11	0.94	0.00	0.00	0.00	0.02	0.09	0.12	0.22	0.67
Greece	1990–1994	0.08	0.01	0.03	0.34	2.20	0.00	0.01	0.02	0.09	0.13	0.22	0.40	0.90
Hungary	1990–1994	0.38	0.02	0.02	0.04	0.95	0.00	0.00	0.00	0.01	0.00	0.00	0.06	0.64
Iceland	1990–1994	0.06	0.00	0.00	0.01	0.26	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Table 13 (continued)

Country / area	*Period*	*Monitored workers (thousands)*	*Measurably exposed workers (thousands)*	*Annual collective effective dose (man Sv)*	*Average annual effective dose (mSv)*		*Distribution ratio [b] (number of workers)*				*Distribution ratio (collective dose)*			
					Monitored workers	*Measurably exposed workers*	NR_{15}	NR_{10}	NR_5	NR_1	SR_{15}	SR_{10}	SR_5	SR_1
Japan	1990–1994	173	45.2	66.1	0.38	1.46	0.00	0.01	0.02	0.08	0.17	0.25	0.41	0.80
Kuwait	1992–1994	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Myanmar	1990–1994	0.04	0.04	0.03	0.75	0.75	0.01	0.01	0.01	0.14				
Netherlands	1990–1993	4.30	0.62	0.41	0.10	0.63	0.00	0.00	0.00	0.02	0.31	0.36	0.39	0.66
Norway	1990–1992	1.51	0.43	0.47	0.31	1.09	0.00	0.00	0.01	0.06				
Pakistan	1990–1994	0.50	0.47	2.38	4.78	5.11	0.09	0.15	0.22	0.39	0.61	0.77	0.87	0.95
Slovakia [g]	1990–1994	0.53	0.09	0.08	0.15	2.01	0.00	0.00	0.01	0.07	0.28	0.34	0.50	0.83
Sri Lanka	1991–1994	0.01	0.01	0.09	9.76	12.1	0.19	0.28	0.28	0.39	0.86	0.96	0.96	0.98
Sweden [x]	1990–1994	7.50		2.38	0.32									
Switzerland	1990–1994	27.7		1.25	0.05		0.00	0.00	0.00	0.01	0.01	0.04	0.16	0.52
Total reported [o p]	1990–1994	461	76.0	98.9	0.21	1.30	0.00	0.00	0.01	0.04	0.15	0.22	0.36	0.74

a Data are annual averages over the periods indicated.
b The values of NR are for the monitored workforce.
c For 1975–1979 the number of workers and the collective dose have been scaled up by a factor of 1.43, since the reported data included only about 70% of the exposed workforce in Australia.
d The method of dose recording was different in the two periods for which data are reported, and this may account partly for the differences in data. Average individual doses for 1975–1979 were calculated from the total of the reported doses for an occupational category divided by the estimated number of workers in that category, with the results rounded to the nearest 1 mSv. In 1990 the estimates were based directly on the results of individual monitoring; in the absence of data for 1985–1989, the data for 1990 have been assumed to be representative of that period.
e Reported data have been rationed up from a sample of approximately 25% of monitored workers.
f The data includes exposures from dental radiography and other medical uses.
g The data for 1975–1989 refer to Czechoslovakia. Scaling down to 60% would give equivalent data for the Czech Republic.
h Where lead aprons are worn the dosemeters are worn below the aprons.
i Reported data contain a contribution from dental radiography.
j Reported data contain a contribution from nuclear medicine.
k The number of workers and the collective dose have been scaled up by a factor of 1.33, since the reported data covered only 75% of those monitored.
l 1980–1989 data from the German Democratic Republic.
m Reported data contain a contribution from radiotherapy.
n Reported data have been rationed up from a sample of approximately 33% of monitored workers.
o The total for measurably exposed workers has been rationed up to take account of countries that did not report the number of measurably exposed workers, but did report a figure for monitored workers.
p These data should be interpreted with care, particularly because the countries included in the summations for the respective five-year periods may not be the same, depending on whether data were reported for the period in question. Consequently, direct comparison between data for different periods is invalid to the extent that the data comprise contributions from different countries. It should also be noted that the data on NR_{15} and SR_{15} are averages of data reported on these ratios. In general, these data are less complete than those that form the basis of the summated number of workers and collective doses.
q The values shown in parentheses are the world estimates based on the standard method given in Section I.E; however, the Committee identified a more robust method of estimation for this instance, based on the regional value for the United States being taken to be equivalent to the rest of OECD. These are the values shown without parentheses.
r Within the data from 1990–1994, the data concerning 1990 only relate to the Federal Republic of Germany.
s Data for dentists in private practice only.
t The data are specifically for the years 1975, 1980 and 1985; they are assumed here to be representative, respectively of 1975–1979, 1980–1984 and 1985–1989.
u In the absence of data for 1985–1989, the data for 1990 have been assumed representative.
v No world estimate has been made because of the undefined nature of the sectors covered.
w The data for 1980–1989 is a combination of data previously reported for the German Democratic Republic and the Federal Republic of Germany.
x These values apply to all medical uses of radiation since no division into different categories could be done.

Table 14
Exposures to workers from all medical uses of radiation [a]
Data from UNSCEAR Survey of Occupational Exposures

Country / area	Period	Monitored workers (thousands)	Measurably exposed workers (thousands)	Annual collective effective dose (man Sv)	Average annual effective dose (mSv)		Distribution ratio [b] (number of workers)				Distribution ratio (collective dose)			
					Monitored worker	Measurably exposed workers	NR_{15}	NR_{10}	NR_5	NR_1	SR_{15}	SR_{10}	SR_5	SR_1
Argentina	1985-1989	3.45	1.20	3.74	1.08	3.12	0.13				0.48			
	1990-1994	6.81		10.39	1.53	3.99	0.04	0.04	0.05	0.18	0.60	0.62	0.68	0.93
Australia [c d]	1975-1979	6.23		3.45	0.55									
	1985-1989	15.80	8.96	1.11	0.07	0.12	0.00				0.04			
	1990-1994	14.77		2.01	0.14	0.23	0.00	0.00	0.00	0.02	0.14	0.15	0.21	0.54
Brazil [e]	1985-1989	76.00	23.00	115.00	1.51	4.96								
	1990-1994	6.39		3.37	0.53	3.32	0.00	0.01	0.02	0.07	0.43	0.54	0.70	0.93
Bulgaria	1990-1994	3.92	0.33	1.75	0.45	4.66	0.00	0.00	0.00	0.04	0.01	0.02	0.05	0.23
Canada	1975-1979	39.6	11.8	10.4	0.26	0.88	0.00				0.08			
	1980-1984	51.7	7.88	8.30	0.16	1.05	0.00				0.04			
	1985-1989	62.90	10.80	9.18	0.15	0.85	0.00				0.06			
	1990-1994	63.65	6.82	5.65	0.09	0.83	0.00	0.00	0.00	0.02	0.07	0.09	0.21	0.67
China	1985-1989	86.80	14.40	156.00	1.80	10.90	0.03				0.43			
	1990-1994	13.96		22.90	1.64	1.76	0.01	0.03	0.05	0.32	0.24	0.33	0.43	0.77
China, Taiwan Province	1980-1984	3.08		1.77	0.57									
	1985-1989	3.98		1.96	0.49									
	1990-1994	6.01	1.35	0.93	0.15	0.69	0.00	0.00	0.00	0.01	0.02	0.02	0.08	0.16
Croatia	1990-1994	3.44	1.89	0.62	0.18	0.33								
Cuba	1990-1994	0.46	0.46	0.99	2.18	2.17	0.01	0.05	0.13	0.71	0.11	0.18	0.31	0.92
Cyprus	1990-1994	0.29	0.17	0.21	0.72	1.26	0.01	0.01	0.02	0.21	0.17	0.21	0.30	0.86
Czech Republic [f]	1975-1979	6.78	1.89	5.16	0.76	2.73	0.00				0.13			
	1980-1984	9.38	3.62	7.80	0.83	2.15	0.00				0.08			
	1985-1989	11.60	4.04	9.12	0.78	2.25	0.00				0.10			
	1990-1994	9.40		7.82	0.83	1.51	0.00	0.00	0.01	0.19	0.05	0.09	0.16	0.69
Denmark	1975-1979	6.13		3.32	0.54		0.00				0.22			
	1980-1984	6.02		2.08	0.35		0.00				0.10			
	1985-1989	6.04		1.18	0.20		0.00				0.01			
	1990-1994	5.28	1.76	1.04	0.20	0.59	0.00	0.00	0.00	0.05	0.01	0.02	0.09	0.60
Ecuador	1990-1994	0.85	0.56	0.70	0.82	1.25	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Table 14 (continued)

Country / area	Period	Monitored workers (thousands)	Measurably exposed workers (thousands)	Annual collective effective dose (man Sv)	Average annual effective dose (mSv)		Distribution ratio [b] (number of workers)				Distribution ratio (collective dose)			
					Monitored worker	Measurably exposed workers	NR_{15}	NR_{10}	NR_5	NR_1	SR_{15}	SR_{10}	SR_5	SR_1
Finland [g]	1975-1979	4.98	0.18	1.17	0.23	6.55	0.00				0.45			
	1980-1984	5.60	0.58	1.23	0.21	2.10	0.00				0.12			
	1985-1989	6.18	0.49	1.22	0.20	2.50	0.00				0.21			
	1990-1994	5.85		1.30	0.22	2.25	0.00	0.00	0.01	0.05	0.24	0.35	0.52	0.89
France	1975-1979	40.9		49.3	1.21		0.00							
	1980-1984	59.2	8.06	36.0	0.61	4.46	0.00							
	1985-1989	73.7	0.42	25.1	0.34	3.06	0.00							
Gabon	1990-1994	0.01	0.00	0.00	0.20		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Germany [h]	1980-1984	158.6	22.2	29.54	0.34	1.18	0.00				0.14			
	1985-1989	209.6	23.19	26.06	0.12	1.12	0.00				0.16			
	1990-1994	230.15		23.86	0.10	0.95	0.00	0.00	0.00	0.02	0.09	0.12	0.22	0.67
Greece	1990-1994	4.81	1.13	4.12	0.86	3.65	0.01	0.02	0.04	0.13	0.42	0.53	0.70	0.93
Hungary	1975-1979	7.80	1.43	3.19	0.41	2.23	0.00				0.16			
	1980-1984	9.15	1.26	2.41	0.26	1.91	0.00				0.13			
	1985-1989	9.07	1.29	2.34	0.26	1.82	0.00				0.11			
	1990-1994	8.38		1.26	0.15	1.38	0.00	0.00	0.00	0.04	0.10	0.14	0.28	0.76
Iceland	1990-1994	0.59	0.14	0.14	0.24	1.01	0.00	0.00	0.01	0.05	0.11	0.22	0.30	0.71
India	1975-1979	9.58	5.22	7.89	0.82	1.51	0.00				0.30			
	1980-1984	11.6	5.74	6.56	0.57	1.14	0.00				0.22			
	1985-1989	15.20	8.03	8.02	0.53	1.00	0.00				0.17			
	1990-1994	16.76		6.38	0.38	0.74	0.00	0.00	0.02	0.08	0.14	0.22	0.37	0.75
Indonesia	1975-1979	1.07	1.02	1.78	1.67	1.75	0.00				0.02			
	1980-1984	2.16	2.06	3.44	1.60	1.68	0.00				0.01			
	1985-1989	2.53	2.41	4.24	1.68	1.77	0.00				0.01			
Ireland	1985-1989	1.69	0.28	0.22	0.13	0.78	0.00				0.00			
	1991-1994	2.86	0.24	0.14	0.05	0.58	0.00	0.00	0.00	0.02	0.00	0.02	0.13	0.52
Italy	1985-1989	44.60	12.60	21.00	0.47	1.66	0.00				0.27			
Japan	1975-1979	55.3	21.7	35.7	0.65	1.65								
	1980-1984	111	34.2	44.0	0.40	1.29								
	1985-1989	142.00	38.60	46.60	0.33	1.21								
	1990-1994	178.4	45.67	66.63	0.37	1.46	0.00	0.01	0.02	0.08	0.17	0.25	0.41	0.80
Jordan	1990-1994	0.49	0.44	0.59	1.21	1.33	0.01	0.02	0.05	0.20	0.19	0.31	0.43	0.71

Table 14 (continued)

Country / area	Period	Monitored workers (thousands)	Measurably exposed workers (thousands)	Annual collective effective dose (man Sv)	Average annual effective dose (mSv)		Distribution ratio [b] (number of workers)				Distribution ratio (collective dose)			
					Monitored worker	Measurably exposed workers	NR_{15}	NR_{10}	NR_5	NR_1	SR_{15}	SR_{10}	SR_5	SR_1
Kuwait	1990–1994	0.62	0.11	0.20	0.33	1.89	0.00	0.00	0.01	0.06	0.15	0.18	0.25	0.58
Mexico	1985–1989	0.73	0.52	2.09	2.86	4.02	0.03				0.24			
	1990–1994	1.27		1.18	0.93									
Myanmar	1990–1994	0.10	0.10	0.08	0.78	0.78	0.01	0.01	0.02	0.18	0.00	0.00	0.00	0.00
Netherlands	1990–1994	19.56	6.11	8.19	0.42	1.34	0.01	0.01	0.02	0.06	0.33	0.45	0.60	0.84
Norway	1990–1994	4.74	1.52	2.90	0.61	1.91	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Pakistan	1990–1994	1.50	1.43	8.10	5.39	5.66	0.13	0.19	0.28	0.50	0.65	0.77	0.88	0.97
Peru	1980–1984	1.58		7.03	4.46									
	1985–1989	1.70		7.14	4.20									
	1990–1994	1.98	1.67	5.34	2.70	3.19	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Portugal	1985–1989	3.83	0.97	2.01	0.52	2.06	0.00							
Slovakia	1990–1994	4.52	0.99	1.58	0.35	1.59	0.00	0.00	0.01	0.10	0.11	0.16	0.30	0.80
Slovenia	1990–1994	2.22	1.76	0.84	0.38	0.48	0.00	0.00	0.00	0.06	0.01	0.01	0.06	0.30
South Africa	1975–1979	8.76	5.49	0.57	0.06	0.10	0.00				0.08			
	1980–1984	10.7	4.13	7.37	0.69	1.79	0.01				0.52			
	1985–1989	12.1	2.64	9.53	0.79	3.61	0.00				0.23			
Spain	1985–1989	37.70	34.00	29.30	0.78	0.86	0.00				0.12			
Sri Lanka	1990–1994	0.37	0.13	0.27	0.73	2.08	0.01	0.01	0.02	0.07	0.46	0.52	0.58	0.77
Sweden	1975–1979	11.5	1.29	2.84	0.25	2.21	0.01							
	1980–1984	12.8	1.38	2.53	0.20	1.83	0.00							
	1985–1989	13.20	3.66	3.13	0.24	0.86	0.00							
	1990–1994	7.79		2.39	0.31									
Switzerland	1975–1979	21.5		6.20	0.29		0.00				0.12			
	1980–1984	30.1		4.97	0.17		0.00				0.09			
	1985–1989	36.10		1.83	0.05		0.00				0.03			
	1990–1994	38.68		1.50	0.04		0.00	0.00	0.00	0.01	0.04	0.06	0.17	0.50
Syrian Arab Republic	1990–1994	0.90	0.08	2.61	2.90	32.63	0.00	0.00	0.00	0.01	0.00	0.00	0.02	0.13

Table 14 (continued)

Country / area	Period	Monitored workers (thousands)	Measurably exposed workers (thousands)	Annual collective effective dose (man Sv)	Average annual effective dose (mSv)		Distribution ratio [b] (number of workers)				Distribution ratio (collective dose)			
					Monitored worker	Measurably exposed workers	NR_{15}	NR_{10}	NR_5	NR_1	SR_{15}	SR_{10}	SR_5	SR_1
Thailand	1990–1994	4.83	1.45	1.03	0.21	0.71	0.00	0.00	0.01	0.04	0.20	0.28	0.43	0.77
United Kingdom [i]	1980–1984	39		28	0.71									
	1985–1989	40.00		8.40	0.21									
	1990–1994	37.81	0.00	4.10	0.11									
United States [j]	1975–1979	485		460	0.95									
	1980–1984	584		410	0.70									
	1985–1989	734	267	280	0.38	1.05								
United Rep. Tanzania	1990–1994	0.44	0.43	2.14	4.91	4.98	0.02	0.16	0.51	0.86	0.06	0.42	0.82	0.98
Reported Total [k l]	1975–1979	671		577	0.86		0.03				0.16			
	1980–1984	1060		588	0.55		0.00				0.11			
	1985–1989	1520		644	0.42		0.01				0.34			
	1990–1994	710	160.00	205	0.29	1.30	0.00	0.00	0.01	0.05	0.21	0.28	0.41	0.77
World estimate [k m]	1975–1979	1280	650	993	0.78	1.50	0.00				0.14			
	1980–1984	1890	520	1140	0.60	1.70	0.00				0.10			
	1989–1989	2220	590	1030	0.47	1.70	0.01				0.24			
	1990–1994	2320	550	760	0.33	1.39	0.00	0.00	0.01	0.06	0.14	0.22	0.35	0.71
		(1850)	(475)	(695)	(0.38)	(1.47)	(0.00)	(0.00)	(0.01)	(0.07)	(0.15)	(0.22)	(0.35)	(0.70)

a Data are annual averages over the periods indicated.
b The values of NR are for the monitored workforce.
c The number of workers and the collective dose have been scaled up by a factor of 1.43, since the reported data included only about 70% of the exposed workforce in Australia.
d The method of dose recording was different in the two periods for which data are reported, and this may account partly for the differences in data. Average individual doses for 1975–1979 were calculated from the total of the reported doses for an occupational category divided by the estimated number of workers in that category, with the results rounded to the nearest 0.1 mSv. In 1990 the estimates were based directly on the results of individual monitoring in the absence of data for 1985–1989, the data for 1990 have been assumed to be representative of that period.
e Reported data have been rationed up from a sample of approximately 25% of monitored workers.
f The data for 1985–1989 refer to Czechoslovakia.
g Reported doses are overestimates because the dosimeter is calibrated in terms of the skin surface dose and is worn above aprons where these are used. For x-ray diagnostic radiology, preliminary studies indicate that the overestimate may be by a factor in the range of 3-30; about 60% of the occupational exposures reported for all medical uses of radiation are currently reported to arise in diagnostic radiology.
h Within the data from 1990–1994, the data concerning 1990 only relate to the Federal Republic of Germany.
i Reported data have been rationed up from a sample of approximately 33% of monitored workers.
j Data for [E1, E2 and E3]. The data are specifically for the years 1975, 1980 and 1985; they are assumed here to be representative, respectively, of 1975–1979, 1980–1984 and 1985–1989.
k The figures quoted are rounded values.
l The total for measurably exposed workers has been rationed up to take account of countries that did not report the number of measurably exposed workers, but did report a figure for monitored workers. Reported data contain a contribution from radiotherapy.
m These data should be interpreted with care, particularly because the countries included in the summations for the respective five-year periods may not be the same, depending on whether the data were reported for the period in question. Consequently, direct comparison between data for different periods is invalid to the extent that the data comprise contributions from different countries. It should also be noted that the data on NR_{15} and SR_{15} are averages of data reported on these ratios. In general, these data are less complete than those that form the basis of the summated number of workers and collective doses.

Table 15
Regional exposures to workers from medical uses of radiation (1990–1994) [a]

Region	*Monitored workers*	*Measurably exposed workers* [b]	*Annual collective effective dose (man Sv)*	*Average annual effective dose (mSv)*		*Distribution ratio* [c] *(number of workers)*				*Distribution ratio (collective dose)*			
				Monitored workers	*Measurably exposed workers*	NR_{15}	NR_{10}	NR_5	NR_1	SR_{15}	SR_{10}	SR_5	SR_1
Diagnostic radiology													
East and South-East Asia	21 415	13 925	22.71	1.06	1.63	0.01	0.02	0.03	0.19	0.24	0.32	0.42	0.75
Eastern Europe	25 291	8 155	9.8	0.39	1.20	0.00	0.00	0.00	0.09	0.06	0.09	0.18	0.65
Indian subcontinent	11 551	6 282	5	0.43	0.80	0.00	0.00	0.02	0.07	0.34	0.41	0.53	0.80
Latin America	12 827	4 776	15.84	1.23	3.32	0.03	0.04	0.05	0.17	0.58	0.61	0.68	0.93
OECD except United States	62 162	20 763	18.66	0.30	0.90	0.00	0.01	0.01	0.06	0.31	0.41	0.56	0.81
Remainder	1 848	1 051	4.64	2.51	4.42	0.01	0.06	0.20	0.40	0.07	0.38	0.74	0.95
Total reported	135 094	54 857	76.7	0.57	1.40	0.01	0.01	0.02	0.10	0.27	0.35	0.46	0.75
Dental radiology													
East and South-East Asia	272	61	0.03	0.11	0.49	0.00	0.00	0.00	0.02	0.16	0.28	0.28	0.71
Eastern Europe	889	168	0.14	0.16	0.83	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.05
Indian subcontinent	730	316	0.11	0.15	0.35	0.00	0.00	0.00	0.03	0.03	0.05	0.15	0.55
Latin America	795	76	0.16	0.20	2.11	0.00	0.00	0.01	0.04	0.42	0.48	0.54	0.66
OECD except United States	78 715	4 671	3.52	0.04	0.75	0.00	0.00	0.00	0.00	0.30	0.36	0.43	0.67
Remainder	33	13	0.01	0.33	0.85	0.01	0.01	0.01	0.08	0.40	0.40	0.40	0.72
Total reported	81 434	5 305	3.97	0.05	0.75	0.00	0.00	0.00	0.00	0.28	0.33	0.40	0.64
Nuclear medicine													
East and South-East Asia	734	320	0.39	0.53	1.22	0.00	0.00	0.01	0.11	0.28	0.32	0.59	0.89
Eastern Europe	2 401	1 607	1.63	0.68	1.01	0.00	0.00	0.01	0.21	0.02	0.04	0.10	0.66
Indian subcontinent	1 099	634	2.61	2.37	4.12	0.06	0.09	0.14	0.29	0.58	0.68	0.83	0.96
Latin America	1 069	632	2.46	2.30	3.89	0.03	0.06	0.12	0.39	0.41	0.48	0.61	0.94
OECD except United States	7 615	3 982	4.91	0.64	1.23	0.00	0.00	0.02	0.24	0.03	0.05	0.18	0.81
Remainder	593	455	0.78	1.32	1.72	0.01	0.02	0.04	0.17	0.15	0.23	0.36	0.62
Total reported	13 511	7 630	12.80	0.95	1.68	0.01	0.02	0.04	0.24	0.24	0.29	0.42	0.81

Table 15 (continued)

Region	*Monitored workers*	*Measurably exposed workers* [b]	*Annual collective effective dose (man Sv)*	*Average annual effective dose (mSv)*		*Distribution ratio* [c] *(number of workers)*				*Distribution ratio (collective dose)*			
				Monitored workers	*Measurably exposed workers*	NR_{15}	NR_{10}	NR_5	NR_1	SR_{15}	SR_{10}	SR_5	SR_1
Radiotherapy													
East and South-East Asia	2 441	1 593	1.78	0.73	1.12	0.01	0.01	0.02	0.24	0.12	0.17	0.28	0.66
Eastern Europe	2 146	1 387	2.14	1.00	1.54	0.00	0.01	0.02	0.26	0.07	0.11	0.19	0.69
Indian subcontinent	4 747	2 515	4.56	0.96	1.81	0.01	0.02	0.05	0.17	0.32	0.43	0.58	0.86
Latin America	1 483	667	2.13	1.44	3.19	0.01	0.02	0.06	0.26	0.44	0.52	0.63	0.93
OECD except United States	8 863	3 187	2.06	0.23	0.65	0.00	0.00	0.00	0.04	0.21	0.24	0.31	0.63
Remainder	160	63	0.29	1.81	4.60	0.01	0.06	0.11	0.25	0.08	0.47	0.76	0.92
Total reported	19 840	9 412	13.0	0.65	1.38	0.00	0.01	0.03	0.15	0.25	0.34	0.46	0.79
All other medical uses													
East and South-East Asia	44	42	0.03	0.68	0.71	0.01	0.01	0.01	0.14				
Eastern Europe	1 154	127	0.16	0.14	1.26	0.00	0.00	0.00	0.04	0.22	0.27	0.41	0.79
Indian subcontinent	508	473	2.47	4.86	5.22	0.09	0.15	0.22	0.39	0.62	0.78	0.87	0.95
Latin America	311	157	0.2	0.64	1.27	0.00	0.00	0.01	0.28	0.00	0.05	0.15	0.82
OECD except United States	458 849	75 199	96	0.21	1.28	0.00	0.00	0.01	0.04	0.15	0.21	0.35	0.76
Remainder	104	36	0.03	0.29	0.83	0.00	0.00	0.00	0.10	0.00	0.00	0.05	0.66
Total reported	460 970	76 034	98.89	0.21	1.30	0.00	0.00	0.01	0.04	0.15	0.22	0.36	0.74
All medical uses													
East and South-East Asia	24 904	15 943	24.94	1.00	1.56	0.01	0.02	0.03	0.19	0.23	0.31	0.41	0.75
Eastern Europe	31 881	11 091	13.87	0.44	1.25	0.00	0.00	0.01	0.09	0.06	0.09	0.17	0.65
Indian subcontinent	18 635	10 220	14.75	0.79	1.44	0.01	0.02	0.04	0.11	0.42	0.52	0.65	0.87
Latin America	16 485	6 308	20.79	1.26	3.30	0.02	0.02	0.03	0.12	0.53	0.57	0.66	0.93
OECD except United States	613 345	112 847	124.58	0.20	1.10	0.00	0.00	0.01	0.04	0.17	0.23	0.38	0.76
Remainder	2 738	1 226	5.752	2.10	4.69	0.01	0.03	0.09	0.21	0.05	0.20	0.38	0.55
Reported Total	707 988	157 635	204.68	0.29	1.30	0.00	0.00	0.01	0.07	0.21	0.28	0.41	0.77

a Data are annual values averaged over the period reported.
b The values for measurably exposed workers has been rationed up to take account of countries that did not report the number of measurably exposed workers, but did report a figure for monitored workers.
c The values of NR are for monitored workers.

Table 16
Summary of worldwide exposures from medical uses of radiation [a]

Practice	*Monitored workers (thousands)*	*Measurably exposed workers (thousands)* [b]	*Annual average collective effective dose (man Sv)*	*Annual average individual dose (mSv)*	
				Monitored workers	*Measurably exposed workers*
1975-1979					
Diagnostic radiology	630		600	0.94	
Dental practice	370		120	0.32	
Nuclear medicine	61		62	1.01	
Radiotherapy	84		190	2.23	
All medicine	1 300		990	0.78	
1980-1984					
Diagnostic radiology	1 100		720	0.68	
Dental practice	500		93	0.19	
Nuclear medicine	81		85	1.04	
Radiotherapy	110		180	1.58	
All medicine	1 900		1 100	0.60	
1985-1989					
Diagnostic radiology	1 400		760	0.56	
Dental practice	480		25	0.05	
Nuclear medicine	90		85	0.95	
Radiotherapy	110		100	0.87	
All medicine	2 200		1 000	0.47	
1990-1994					
Diagnostic radiology [c]	950	350	470	0.50	1.34
	(840)	(330)	(485)	(0.57)	(1.47)
Dental practice [c]	265	17	16	0.06	0.89
	(240)	(17)	(13)	(0.04)	(0.77)
Nuclear medicine [c]	115	65	90	0.79	1.41
	(100)	(60)	(86)	(0.86)	(1.40)
Radiotherapy [c]	120	48	65	0.55	1.33
	(105)	(52)	(72)	(0.68)	(1.39)
Other uses	870	70	119	0.14	1.70
	(555)	(16)	(39)	(0.07)	(2.44)
All medicine [c]	2 320	550	760	0.33	1.39
	(1 840)	(475)	(695)	(0.38)	(1.47)

a The data are annual values averaged over the respective five year periods and are, in general, quoted to two significant figures.
b The total for measurably exposed workers has been rationed up to take account of countries that did not report the number of measurably exposed workers, but did report a figure for monitored workers.
c The values shown in brackets are the world estimates based on the standard method given in Section I.E; however the Committee identified a more robust method of estimation for this instance, based on the regional value for the United States being taken to be equivalent to the rest of OECD (see para 156).

Table 17
Worldwide exposure from all medical uses of radiation [a]

Region	Monitored workers (thousands)	Measurably exposed workers (thousands)	Average annual collective dose (man Sv)	Average annual individual dose to monitored workers (mSv)	Average annual individual dose to measurably exposed workers (mSv)	Collective effective dose [b] per unit GDP (man Sv per 10^{12} US$)
1975–1979						
East and South-East Asia	4		70	1.7		44
Eastern Europe [c]	190		110	0.57		94
Indian subcontinent	12		10	0.82		81
Latin America						
OECD except United States	360		220	0.61		74
United States (estimate) [d]	490		460	0.95		250
Remainder	230		190	0.84		160
Total	1 300		990	0.78		130
1980–1984						
East and South-East Asia	10		16	1.6		37
Eastern Europe [c]	460		150	0.31		64
Indian subcontinent	15		9	0.57		33
Latin America	60		270	4.5		350
OECD except United States	610		210	0.35		43
United States (estimate) [d]	580		410	0.70		120
Remainder	160		90	0.55		79
Total	1 900		1 100	0.60		87
1985–1989						
Asia	96		170	1.8		440
East and South-East Asia	17		29	1.7		56
Eastern Europe [c]	430		130	0.31		38
Indian subcontinent	19		10	0.53		30
Latin America	110		180	1.6		220
OECD except United States	740		190	0.27		24
United States (estimate) [d]	730		280	0.38		58
Remainder	75		35	0.47		56
Total	2 200		1 000	0.47		54
1990–1994						
East and South-East Asia	44	28	45	1.00	1.56	40
Eastern Europe	420	145	182	0.44	1.25	105
Indian subcontinent	26	14	21	0.79	1.44	41
Latin America	22	9	28	1.26	3.30	32
OECD except United States	870	160	180	0.20	1.10	16
United States [d]	870	160	180	0.20	1.10	16
	(400)	(90)	(115)			21
Remainder	61	27	127	2.10	4.69	94
World	2 320 (1 850)	550 (475)	760 (695)	0.33 (0.38)	1.39 (1.47)	34 (31)

a The data are annual averages over the respective five year periods and are, in general, quoted to two significant figures.
b The normalized collective doses per unit GDP for the three five year periods are expressed, respectively, in terms of 1977, 1983, 1989 and 1994 prices; direct comparison between the values for different periods is possible only after correcting for these different price bases.
c Including the whole of the former USSR.
d The values shown in brackets are the world estimates based on the standard method given in Section I.E; however the Committee identified a more robust method of estimation for this instance, based on the regional value for the United States being taken to be equivalent to the rest of OECD (see para 156).

Table 18
Exposures to medical staff involved in diagnostic radiology in the United Kingdom in 1991
[H3]

Occupational group	*Number of workers in dose range*				*Total number of workers*	*Annual collective dose (man Sv)*	*Average annual dose (mSv)*
	0 –1 mSv	*1 –5 mSv*	*5 –15 mSv*	*>15 mSv*			
Radiographers	5 663	55	1	0	5 719	0.28	0.05
Radiologists	7 29	38	0	0	767	0.14	0.18
Cardiologists	1 71	22	2	1	196	0.089	0.44
Other clinicians	4 65	9	0	0	474	0.044	0.09
Nurses	1 522	38	1	0	1 561	0.13	0.08
Technicians	1 070	27	1	0	1 098	0.090	0.08
Other	937	5	2	0	944	0.053	0.06

Table 19
Trend in occupational exposures in Spain from 1989 to 1995
[H8]

Occupational category	*Total number of workers*		*Average annual individual dose (mSv)*		*Collective dose (man Sv)*		*Number of individual dose >20 mSv*	
	1989	*1995*	*1989*	*1995*	*1989*	*1995*	*1989*	*1995*
Medical uses of radiation								
Diagnostic radiology	33 036	41 583	0.82	0.53	26.4	19.7		15
Radiotherapy	1 041	1 614	0.91	0.57	0.9	0.9		1
Nuclear medicine	924	1 546	1.93	1.35	1.6	2.0		1
Dental radiology	1 294	4 631	1.29	0.60	1.6	2.1		2
Other	-	7 196	-	0.42	-	2.7		3
Total	37 750	56 570	0.86	0.55	47	27.4	90	22
Industrial uses of radiation								
Radiography	650	440	1.10	2.46	0.6	0.7		0
Gammagraphy	169	327	4.52	2.59	0.7	0.7		4
Process control	672	1 871	1.58	0.99	0.9	1.6		2
Metrology		350		1.32		0.1		0
Manufacturing		1 045		1.14		1.1		0
Other		1 037		1.26		1.1		7
Total	3 031	5 070	1.6	1.3	5.3	5.6	17	13
Nuclear fuel cycle								
Reactor operation	10 807	8 765	2.7	3.1	20.6	16.0	88	93
Other fuel cycle operation	757	807	1.2	0.3	0.6	0.1	0	0
Research/transport	-	4 778	-	0.7	-	2.7	-	4
Total	11 564	14 350	1.8	1.3	21.2	18.8	88	97
All uses of radiation								
Total	52 345	75 990			73.5	51.8	195	132

Table 20
Medical occupational exposures in France in 1995
[C3]

Occupational category	*Monitored workers*	*Collective dose (man Sv)*	*Individual dose >20 mSv a^{-1}*	*Individual dose >50 mSv a^{-1}*
Radiology	86 607	13.0	104	31
Radiotherapy	8 528	2.0	11	1
Nuclear medicine	3 998	1.5	3	0
In vitro unsealed sources	4 669	0.09	0	0
Dental radiology	19 759	1.0	6	3
Occupational medicine	6 172	0.39	1	1
Veterinary uses	2 959	0.27	2	1
Total	132 692	18.3	127	37

Table 21
Exposures to medical staff involved in radiotherapy in the United Kingdom in 1991
[H3]

Occupational group	*Numbers of workers in dose range*				*Total number of workers*	*Annual collective dose (man Sv)*	*Average annual dose (mSv)*
	0–1 mSv	*1–5 mSv*	*5–10 mSv*	*>10 mSv*			
Beam radiographers	541	15	0	0	556	0.038	0.07
Radiotherapists	192	6	0	0	198	0.019	0.09
Sealed-source technicians	8	1	0	0	9	0.001	0.12
Radiotherapy theatre nurses	9	1	0	0	10	0.003	0.28
Brachytherapy ward nurses	548	5	3	0	556	0.053	0.10
Other nurses	203	9	1	0	213	0.051	0.24
Technicians	130	1	0	0	131	0.008	0.06
Other	354	6	0	0	360	0.028	0.08

Table 22
Exposures to workers from industrial uses of radiation [a]

Country / area	Period	Monitored workers (thousands)	Measurably exposed workers (thousands)	Annual collective effective dose (man Sv)	Average annual effective dose (mSv)		Distribution ratio [b] (number of workers)				Distribution ratio (collective dose)			
					Monitored workers	Measurably exposed workers	NR_{15}	NR_{10}	NR_5	NR_1	SR_{15}	SR_{10}	SR_5	SR_1
Industrial irradiation [c]														
Argentina	1990–1994	0.03	0.03	0.03	1.14	1.28	0.01	0.03	0.03	0.25	0.13	0.31	0.31	0.69
Australia	1990–1994	1.23	0.43	0.35	0.29	0.81	0.00	0.00	0.01	0.05	0.38	0.40	0.57	0.87
Canada	1990–1994	0.01	< 0.01	0.00	0.05	0.21	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
China	1992–1994	0.10	0.09	0.10	1.03	1.06	0.00	0.01	0.01	0.15	0.00	0.01	0.01	0.55
Cuba	1990–1994	0.03	0.03	0.04	1.27	1.29	0.00	0.00	0.00	0.41	0.00	0.00	0.00	0.68
Ecuador	1993–1994	0.01	0	0.00	0.00		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Finland [d]	1990–1994	0.76	0.04	0.06	0.08	1.54	0.00	0.00	0.00	0.02	0.00	0.07	0.36	0.82
Iceland	1990–1994	0.02	0		0.00		0.00	0.00	0.00	0.00				
Ireland	1991–1994	0.05	0.01	0.00	0.01	0.02	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Japan	1990–1994	54.9	1.79	4.95	0.09	2.76	0.00	0.00	0.00	0.01	0.43	0.55	0.74	0.93
Mexico	1990–1994	0.06		0.03	0.48									
Netherlands	1990–1994	0.01	< 0.01		0.00	0.14	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Poland	1992–1994	0.02	0.02	0.02	0.84	0.86	0.00	0.00	0.00	0.50	0.00	0.00	0.00	0.60
Sri Lanka	1994	0.02	0.01	0.00	0.09	0.15	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Syrian Arab Republic	1994	0.01	< 0.01	0.01	0.42	1.40	0.00	0.00	0.00	0.09	0.00	0.00	0.00	0.64
Total reported data [e]	1990–1994	57.2	2.45	5.96	0.10	2.28	0.00	0.00	0.00	0.01	0.41	0.52	0.70	0.91
Industrial radiography														
Argentina	1985–1989	0.05	0.01	0.03	0.59	2.7								
	1990–1994	0.33	0.09	0.27	0.83	2.90	0.01	0.02	0.04	0.14	0.30	0.41	0.56	0.92
Australia	1985–1989	0.40	0.26	0.40	1.01	1.52	0.01				0.11			
	1990–1994	2.51	1.02	0.47	0.19	0.46	0.00	0.00	0.01	0.04	0.04	0.12	0.29	0.73
Brazil [f]	1985–1989				3.30	14.5								
	1990–1994	0.90	0.41	1.26	1.40	3.13	0.01	0.02	0.06	0.27	0.32	0.39	0.59	0.94
Bulgaria [g]	1990–1994	0.69	0.17	0.60	0.87	1.63	0.00	0.00	0.01	0.12	0.03	0.04	0.08	0.35
Canada	1975–1979	1.07	0.71	4.33	4.05	6.08	0.08				0.51			
	1980–1984	1.46	0.76	4.88	3.35	6.41	0.06				0.50			
	1985–1989	1.43	0.84	6.47	4.51	7.75	0.09				0.57			
	1990–1994	2.23	1.30	7.55	3.39	5.82	0.06	0.11	0.21	0.41	0.42	0.60	0.83	0.98
China	1990–1994	2.75	2.38	3.47	1.26	1.45	0.01	0.02	0.05	0.20	0.19	0.31	0.44	0.71
China, Taiwan Province	1985–1989	1.01		1.53	1.52									
	1990–1994	2.39	1.09	0.91	0.38	0.84								

Table 22 (continued)

Country / area	*Period*	*Monitored workers (thousands)*	*Measurably exposed workers (thousands)*	*Annual collective effective dose (man Sv)*	*Average annual effective dose (mSv)*		*Distribution ratio [b] (number of workers)*				*Distribution ratio (collective dose)*			
					Monitored workers	*Measurably exposed workers*	NR_{15}	NR_{10}	NR_5	NR_1	SR_{15}	SR_{10}	SR_5	SR_1
Croatia	1990–1994	0.04	0.02	0.05	1.43	2.50								
Cuba	1990–1994	0.20	0.20	0.24	1.25	2.08	0.00	0.00	0.02	0.36	0.03	0.04	0.09	0.44
Czech Republic	1975–1979	0.54		1.24	2.31		0.03				0.31			
	1980–1984	1.03		2.19	2.12		0.02				0.16			
	1985–1989	1.32		2.15			0.01				0.14			
	1990–1994	1.12	0.88	1.75	1.56	1.98	0.01	0.03	0.09	0.41	0.10	0.24	0.50	0.89
Denmark	1975–1979	0.24		0.23	0.98		0.00				0.08			
	1980–1984	0.33		0.43	1.33		0.00				0.12			
	1985–1989	0.41		0.48	1.19		0.00				0.08			
	1990–1994	0.39	0.21	0.40	1.03	1.93	0.00	0.01	0.06	0.27	0.03	0.11	0.41	0.90
Ecuador	1993–1994	0.02	0.01	0.03	1.16	2.36	0.00	0.00	0.04	0.38				
Finland	1980–1984		0.03	0.05		1.51								
	1985–1989		0.06	0.11		1.65								
	1990–1994	0.35	0.09	0.09	0.26	1.02	0.00	0.00	0.00	0.07	0.07	0.10	0.16	0.67
France	1975–1979	1.28		1.47	1.15						0.03			
	1985–1989	1.60	0.09	0.28	0.18	3.11	0.00							
Gabon	1992–1994	0.00	0.00	0.08	20.48	20.48	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Germany [h]	1980–1984	2.09	0.43	0.83	0.40	1.93	0.00			0.17				
	1985–1989	6.82	2.04	7.93	1.16	3.89	0.02			0.30				
	1990–1994	6.66	2.19	9.41	1.41	4.29	0.02	0.04	0.09	0.21	0.30	0.48	0.73	0.96
Greece	1990–1994	0.24	0.03	0.06	0.26	2.50	0.00	0.00	0.01	0.05	0.20	0.34	0.61	0.90
Hungary	1975–1979	1.13	0.41	2.54	2.25	6.13	0.03				0.40			
	1980–1984	1.24	0.39	1.47	1.19	3.79	0.01				0.22			
	1985–1989	1.16	0.37	1.15	0.99	3.14	0.01				0.13			
	1990–1994	0.76	0.23	0.64	0.84	2.78	0.01	0.01	0.05	0.19	0.09	0.21	0.50	0.92
Iceland	1990–1994	0.01	0.00	0.00	0.04	0.14	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
India	1980–1984	2.93	1.39	9.0	3.07	6.50	0.06				0.55			
	1985–1989	4.23	2.12	13.2	3.12	6.10	0.06				0.54			
	1990–1994	3.68	1.92	6.77	1.84	3.49	0.03	0.05	0.10	0.27	0.37	0.53	0.73	0.95

Table 22 (continued)

Country / area	Period	Monitored workers (thousands)	Measurably exposed workers (thousands)	Annual collective effective dose (man Sv)	Average annual effective dose (mSv)		Distribution ratio [b] (number of workers)				Distribution ratio (collective dose)			
					Monitored workers	Measurably exposed workers	NR_{15}	NR_{10}	NR_5	NR_1	SR_{15}	SR_{10}	SR_5	SR_1
Indonesia	1980–1984	0.14	0.02	0.22	1.53	10.8	0.03				0.45			
	1985–1989	0.43	0.03	0.40	0.95	14.9	0.06				0.10			
	1990–1994													
Ireland	1980–1984	0.07	0.04	0.05	0.75	1.39								
	1985–1989	0.05	0.03	0.06	1.41	2.57	0.01				0.15			
	1990–1994	0.09	0.02	0.03	0.35	1.58	0.00	0.00	0.03	0.12	0.00	0.00	0.35	0.79
Japan	1980–1984	3.31	1.58	5.67	1.71	3.59	0.02							
	1985–1989	2.83	1.08	3.35	1.19	3.09	0.01							
	1990–1994	4.35	1.41	4.00	0.83	2.57	0.01	0.02	0.05	0.15	0.24	0.38	0.62	0.93
Kuwait	1992–1994	0.13	0.03	0.60	0.47	1.98	0.00	0.00	0.02	0.10	0.00	0.00	0.28	0.72
Mexico	1985–1989	0.82	0.49	5.10	6.23	10.5	0.10				0.67			
	1990–1994	0.87		4.83	5.58									
Myanmar	1994	0.00	0.00	0.00	0.75	0.75	0.00	0.00	0.00	0.50				
Netherlands [i]	1980–1984	0.97		0.34	0.35		0.00				0.13			
	1985–1989	1.02		0.48	0.47		0.00				0.20			
	1990–1994	1.00	0.64	1.52	1.52	2.38	0.01	0.02	0.07	0.33	0.19	0.25	0.50	0.92
New Zealand	1980–1984	0.15		0.35	2.33									
Norway	1980–1984	0.80	0.44	0.79	0.99	1.81	0.00				0.04			
	1985–1989	0.82	0.40	0.62	0.76	1.56	0.00				0.10			
	1990–1994	1.11	0.26	0.31	0.28	1.19	0.00	0.00	0.01	0.09				
Pakistan	1990–1994	0.11	0.10	0.58	5.19	5.92	0.13	0.17	0.24	0.48	0.67	0.74	0.85	0.96
Peru	1994	0.04	0.03	0.18	5.00	6.73	0.00	0.00	0.11	0.20				
Poland	1992–1994	0.80	0.77	2.36	2.96	3.07	0.03	0.05	0.11	0.86	0.24	0.36	0.49	0.97
Slovakia	1990–1994	0.47	0.26	0.56	1.19	2.08	0.00	0.01	0.04	0.32	0.04	0.09	0.32	0.88
Slovenia	1993–1994	0.09	0.09	0.11	1.29	1.30	0.01	0.02	0.06	0.25	0.15	0.22	0.46	0.77
South Africa	1975–1979	0.57	0.31	0.11	0.19	0.35								
	1980–1984	0.75	0.45	2.38	3.18	5.30	0.05				0.44			
	1985–1989	0.72	0.32	1.68	2.33	5.29	0.03				0.36			

Table 22 (continued)

Country / area	Period	Monitored workers (thousands)	Measurably exposed workers (thousands)	Annual collective effective dose (man Sv)	Average annual effective dose (mSv)		Distribution ratio [b] (number of workers)				Distribution ratio (collective dose)			
					Monitored workers	Measurably exposed workers	NR_{15}	NR_{10}	NR_5	NR_1	SR_{15}	SR_{10}	SR_5	SR_1
Spain	1985–1989	0.82	0.66	1.23	1.50	1.87	0.02				0.32			
Sri Lanka	1990–1994	0.03	0.01	0.03	1.00	2.12	0.01	0.02	0.03	0.12	0.49	0.70	0.73	0.92
Sweden	1975–1979	0.77	0.19	0.49	0.63	2.56	0.01				0.16			
	1980–1984	0.66	0.17	0.38	0.57	2.27	0.00				0.06			
	1985–1989	0.64	0.25	0.28	0.43	1.12	0.00				0.15			
Syrian Arab Republic	1990–1994	0.06	0.01	0.01	0.20	1.36	0.00	0.00	0.00	0.02	0.00	0.00	0.11	0.37
Thailand	1990–1994	2.28	0.23	1.77	0.78	7.85	0.02	0.02	0.03	0.06	0.70	0.80	0.90	0.99
United Kingdom [j]	1980–1984	1.82		3.60	1.98		0.02							
	1985–1989	4.82	4.08	5.67	1.18	1.39	0.01				0.43			
	1990–1994	5.10	2.49	3.86	0.76	1.55	0.01	0.01	0.03	0.11				
United Rep. of Tanzania [k]	1990–1994	0.03	0.02	0.08	2.46	3.56	0.00	0.01	0.19	0.43	0.00	0.03	0.47	0.90
United States [l]	1975–1979	17		50	2.94									
	1980–1984	27		80	2.96									
	1985–1989	23	12	39	1.70	3.25								
	1990–1994	5.60	3.75	18.3	3.27	5.68	0.03	0.10	0.20	0.42	0.29	0.60	0.82	0.98
USSR	1975–1979	2.27		30.0	13.2									
	1980–1984	2.53		20.2	7.98									
	1985–1989	2.63		17.2	6.55									
Total of reported data [m]	1975–1979	24.0		89.5	3.74		0.04				0.39			
	1980–1984	42.1		125	2.98		0.03				0.42			
	1985–1989	49.9		98.7	1.98		0.03				0.44			
	1990–1994	47.4	22.67	73.2	1.54	3.23	0.02	0.04	0.08	0.23	0.30	0.49	0.70	0.93
World [n]	1975–1979	72		190	2.61									
	1980–1984	116		230	1.98									
	1985–1989	108		160	1.44									
	1990–1994	106	53	170	1.58	3.17	0.01	0.03	0.07	0.27	0.23	0.36	0.57	0.89
Luminizing [c]														
Canada	1990–1994	0.02	0.01	0.01	0.54	1.17	0.00	0.00	0.00	0.18	0.00	0.00	0.00	0.73
China	1992	0.04	0.04	0.01	0.28	0.28	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Table 22 (continued)

Country / area	Period	Monitored workers (thousands)	Measurably exposed workers (thousands)	Annual collective effective dose (man Sv)	Average annual effective dose (mSv)		Distribution ratio [b] (number of workers)				Distribution ratio (collective dose)			
					Monitored workers	Measurably exposed workers	NR_{15}	NR_{10}	NR_5	NR_1	SR_{15}	SR_{10}	SR_5	SR_1
France	1975–1979	0.07		0.38	5.30						0.66			
	1980–1984	0.04		0.24	5.52		0.14				0.55			
	1985–1989	0.03		0.18	6.84		0.17				0.52			
	1990–1994													
India [o]	1980–1984	0.07	0.03	0.08	1.16	2.78	0.01				0.16			
	1985–1989	0.15	0.06	0.19	1.26	3.37	0.02				0.54			
	1990–1994													
South Africa [p]	1990–1994	0.02	0.02	0.01	0.88	0.96	0.00	0.00	0.04	0.22	0.00	0.00	0.28	0.78
Switzerland	1975–1979	0.21		2.31	11.2		0.25				0.53			
	1980–1984	0.13		1.02	7.82		0.14				0.39			
	1985–1989	0.16		0.68	4.31		0.04				0.18			
United Kingdom (paint)	1975–1979	0.09		0.40	4.32									
United Kingdom (tritium)	1975–1979	0.25		1.50	5.89		0.12				0.65			
	1980–1984	0.33		1.10	3.33		0.06				0.40			
Total reported data [m]	1975–1979	0.51		3.77	7.44		0.18				0.58			
	1980–1984	0.27		1.34	5.01		0.08				0.37			
	1985–1989	0.54		1.45	2.71		0.03				0.31			
	1990–1994	0.08		0.03	0.38		0.00	0.00	0.01	0.10	0.00	0.00	0.09	0.50
Radioisotope production														
Argentina	1975–1979	0.17		0.67	4.05									
	1980–1984	0.22		0.45	2.10									
	1985–1989	0.18		0.44	2.47									
	1990–1994	0.16	0.14	0.38	2.47	2.69	0.02	0.04	0.12	0.52	0.22	0.31	0.49	0.93
Australia	1990–1994	0.09		0.26	2.99		0.03	0.09	0.27		0.18	0.52	0.93	
Canada [q]	1975–1979	0.05	0.03	0.12	2.67	3.84	0.02				0.14			
	1980–1984	0.03	0.03	0.19	5.83	7.28	0.09				0.41			
	1985–1989	0.30	0.16	0.48	1.61	2.94	0.01				0.18			
	1990–1994	0.40	0.23	0.57	1.44	2.45	0.00	0.02	0.08	0.35	0.05	0.17	0.48	0.93
China	1990–1994	0.35	0.32	1.43	4.10	4.46	0.07	0.12	0.21	0.50	0.50	0.63	0.80	096
Czech Republic	1975–1979	0.18		0.50	2.76		0.02				0.19			
	1980–1984	0.33		0.60	1.80		0.02				0.30			
	1985–1989	0.40		0.81	2.05		0.04				0.42			
	1990–1994	0.10	0.08	0.09	0.89	1.14	0.00	0.00	0.03	0.32	0.00	0.00	0.18	0.72

Table 22 (continued)

Country / area	Period	Monitored workers (thousands)	Measurably exposed workers (thousands)	Annual collective effective dose (man Sv)	Average annual effective dose (mSv)		Distribution ratio [b] (number of workers)				Distribution ratio (collective dose)			
					Monitored workers	Measurably exposed workers	NR_{15}	NR_{10}	NR_5	NR_1	SR_{15}	SR_{10}	SR_5	SR_1
Finland [r]	1975–1979		0.00	0.01		4.23								
	1980–1984		0.00	0.02		3.92								
	1985–1989		0.01	0.05		4.10								
	1990–1994													
Hungary	1975–1979	0.21	0.08	0.27	1.33	3.49	0.01				0.21			
	1980–1984	0.25	0.09	0.30	1.18	3.35	0.01				0.10			
	1985–1989	0.24	0.09	0.32	1.31	3.56	0.01				0.16			
	1990–1994	0.10	0.05	0.16	1.55	2.97	0.00	0.01	0.09	0.37	0.02	0.10	0.47	0.94
India	1980–1984	0.40	0.31	0.67	1.69	2.20	0.01				0.17			
	1985–1989	0.51	0.35	0.71	1.39	2.02	0.01				0.14			
	1990–1994	0.53	0.37	0.73	1.39	1.98	0.01	0.03	0.07	0.28	0.23	0.33	0.52	0.85
Indonesia	1975–1979	0.03		0.11	4.34									
	1980–1984	0.03	0.03	0.06	1.76	2.03								
	1985–1989	0.05	0.04	0.08	1.81	2.10								
	1990–1994													
Netherlands [i]	1985–1989	0.18		0.87	4.97		0.04				0.13			
	1990–1994	0.21	0.19	0.94	4.41	4.85	0.05	0.13	0.36	0.65	0.21	0.42	0.79	0.97
Pakistan	1990–1994	0.02	0.02	0.04	1.81	1.82	0.00	0.03	0.03	0.61	0.00	0.09	0.30	0.83
Peru	1994	0.03	0.02	0.13	5.00	5.21	0.08	0.20	0.32	0.84				
Poland	1992–1994	0.20	0.19	0.27	1.39	1.46	0.00	0.01	0.03	0.78	0.04	0.07	0.21	0.92
Republic of Korea	1975–1979	0.02	0.02	0.12	5.22	6.00	0.10				0.32			
	1980–1984	0.02	0.02	0.15	7.43	7.65	0.34				0.64			
	1985–1989	0.02	0.01	0.09	5.38	6.52	0.06				0.17			
South Africa	1975–1979	0.02		0.16	8.74		0.23				0.71			
	1980–1984	0.30		0.16	5.27		0.10				0.57			
	1985–1989	0.03		0.18	5.75		0.12				0.52			
	1990–1994	0.10	0.06	0.26	2.55	5.63	0.04	0.09	0.15	0.35	0.28	0.69	0.82	0.96
Thailand	1990–1994	0.04	0.03	0.04	1.15	1.48	0.00	0.01	0.02	0.43	0.00	0.06	0.12	0.81
United Kingdom	1975–1979	0.97		6.39	6.59		0.14							
	1980–1984	1.26		4.82	3.84		0.07							
	1985–1989	1.72		4.63	2.70		0.03							
	1991	1.22		2.40	1.96									

Table 22 (continued)

Country / area	Period	Monitored workers (thousands)	Measurably exposed workers (thousands)	Annual collective effective dose (man Sv)	Average annual effective dose (mSv)		Distribution ratio [b] (number of workers)				Distribution ratio (collective dose)			
					Monitored workers	Measurably exposed workers	NR_{15}	NR_{10}	NR_5	NR_1	SR_{15}	SR_{10}	SR_5	SR_1
United States	1975–1979	20		40	2.00									
	1980–1984	29		30	1.03									
	1985–1989	30	17	25	0.83	1.47								
	1990–1994	4.45	2	6.92	1.56	4.69	0.02	0.05	0.07	0.16	0.49	0.75	0.88	0.97
Total reported data [m]	1975–1979	21.6		48.3	2.23		0.10				0.18			
	1980–1984	31.5		37.3	1.18		0.05				0.23			
	1985–1989	33.2		32.7	0.98		0.03				0.23			
	1990–1994	7.98	4.46	14.6	1.83	3.28	0.02	0.05	0.09	0.25	0.39	0.60	0.78	0.95
World [n]	1975–1979	57		130	2.25									
	1980–1984	82		100	1.26									
	1985–1989	88		98	1.12									
	1990–1994	24	16	47	1.93	2.95	0.02	0.04	0.10	0.41	0.25	0.42	0.64	0.94
Well-logging [c]														
Australia	1990–1994	4.71	1.66	0.17	0.04	0.10	0	0	0	0	0	0	0.02	0.10
Canada	1975–1979	0.45	0.21	0.52	1.16	2.43	0.01				0.17			
	1980–1984	1.01	0.58	1.28	1.27	2.21	0.01				0.11			
	1985–1989	1.11	0.74	1.37	1.24	1.85	0.00				0.05			
	1990–1994	0.95	0.58	0.94	0.99	1.90	0.00	0.00	0.03	0.30	0.08	0.11	0.30	0.85
China	1990–1994	0.34	0.34	0.48	1.40	1.41	0.01	0.01	0.02	0.56	0.15	0.19	0.23	0.86
Croatia	1990–1994	0.08	0.01	0.01	0.13	1.00								
Cuba	1990–1994	0.08	0.08	0.12	1.60	1.60	0.00	0.00	0.00	0.70	0.00	0.00	0.00	0.88
Czech Republic	1975–1979	0.06		0.06	1.02									
	1980–1984	0.09		0.15	1.60		0.00				0.03			
	1985–1989	0.11		0.20	1.72		0.00				0.02			
	1990–1994	0.12	106	0.24	2.05	2.26	0.00	0.01	0.08	0.73	0.00	0.07	0.26	0.96
Ecuador	1993–1994	0.11	0.11	0.16	1.45	1.45	0.00	0.00	0.01	.066				
Iceland	1990–1994	0.01	0.00		0.00		0.00	0.00	0.00	0.00				
India [s]	1980–1984	0.19	0.04	0.07	0.38	1.75	0.01				0.39			
	1985–1989	0.64	0.30	0.38	0.54	1.25	0.00				0.09			
	1990–1994	0.87	0.51	0.45	0.51	0.87	0.00	0.00	0.01	0.15	0.02	0.05	0.15	0.65

Table 22 (continued)

Country / area	*Period*	*Monitored workers (thousands)*	*Measurably exposed workers (thousands)*	*Annual collective effective dose (man Sv)*	*Average annual effective dose (mSv)*		*Distribution ratio* [b] *(number of workers)*				*Distribution ratio (collective dose)*			
					Monitored workers	*Measurably exposed workers*	NR_{15}	NR_{10}	NR_5	NR_1	SR_{15}	SR_{10}	SR_5	SR_1
Indonesia	1980–1984 1985–1989	0.14 0.56	0.04 0.45	0.12 0.84	0.82 1.51	3.07 1.89								
Kuwait	1992–1994	0.03	0.00	0.01	0.20	3.2	0.00	0.00	0.01	0.01	0.00	0.00	0.45	0.45
Mexico	1985–1989 1990–1994	0.36 0.48	0.01	0.00 0.07	0.01 0.15	0.32								
Myanmar	1994	0.00	0.00	0.00	0.65	0.65	0.00	0.00	0.00	0.50				
Norway	1990–1992	0.35	0.03	0.00	0.01	0.15	0.00	0.00	0.00	0.00				
Peru	1994	0.10	0.09	0.04	0.40	0.45	0.00	0.00	0.00	0.00				
Poland	1992–1994	0.16	0.15	0.15	0.97	1.01	0.00	0.00	0.01	0.81	0.00	0.02	0.06	0.90
Slovakia	1990–1994	0.04	0.03	0.22	5.25	8.55	0.09	0.27	0.43	0.57	0.29	0.70	0.90	0.99
Slovenia	1993–1994	0.00	0.00	0.00	1.54	1.54	0.00	0.00	0.00	0.67				
South Africa	1975–1979 1980–1984 1985–1989	0.04 0.04 0.04	0.01 0.02 0.01	0.00 0.06 0.05	0.01 1.61 1.49	0.03 3.76 4.55								
United States [t]	1975–1979	7.6		10.3	1.36						0.3			
Total reported data [m]	1975–1979 1980–1984 1985–1989 1990–1994	 8.43	 3.87	 3.06	1.32 1.17 1.07 0.36	 0.79	0.01 0.00 0.00 0.00	 0.00	 0.01	 0.12	0.27 0.10 0.04 0.08	 0.14	 0.27	 0.79
Accelerator operation [c]														
Argentina	1990–1994	0.03	0.02	0.00	0.09	0.12	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Canada	1975–1979 1980–1984 1985–1989 1990–1994	0.58 0.88 1.00 0.99	0.19 0.23 0.53 0.40	0.17 0.40 1.06 0.77	0.30 0.45 1.06 0.77	0.91 1.76 2.00 1.94	0.00 0.00 0.00 0.00	 0.01	 0.05	 0.17	0.10 0.04 0.07 0.03	 0.10	 0.50	 0.89
China	1990–1994	0.02	0.00	0.02	1.04	1.71	0.00	0.00	0.05	0.26	0.00	0.00	0.37	0.91
Ecuador	1993–1994	0.01	0	0.00	0.00		0.00	0.00	0.00	0.00				

Table 22 (continued)

Country / area	*Period*	*Monitored workers (thousands)*	*Measurably exposed workers (thousands)*	*Annual collective effective dose (man Sv)*	*Average annual effective dose (mSv)*		*Distribution ratio* [b] *(number of workers)*				*Distribution ratio (collective dose)*			
					Monitored workers	*Measurably exposed workers*	NR_{15}	NR_{10}	NR_5	NR_1	SR_{15}	SR_{10}	SR_5	SR_1
Finland	1980–1984		0.01	0.01		1.23								
	1985–1989		0.01	0.01		1.23								
	1990–1994	0.08	0.01	0.01	0.08	1.21	0.00	0.00	0.00	0.04	0.00	0.00	0.00	0.83
Netherlands	1980–1984	0.18	0.01	0.01	0.03	0.67								
	1985–1989	0.16	0.01	0.00	0.03	0.46								
Poland	1992–1994	0.14	0.13	0.14	0.95	1.04	0.00	0.00	0.01	0.48	0.05	0.09	0.11	0.68
Slovakia	1990–1994	0.02	0.01	0.04	1.68	2.70	0.00	0.02	0.11	0.33	0.00	0.12	0.47	0.89
Slovenia	1990–1994	0.01	0.01	0.00	0.51	0.51	0.00	0.00	0.00	0.02	0.00	0.00	0.00	0.04
South Africa	1975–1979	0.07	0.03	0.03	0.46	1.00								
	1980–1984	0.10	0.04	0.27	2.72	6.59	0.05				0.55			
	1985–1989	0.22	0.07	0.34	1.56	4.76	0.04				0.61			
United Kingdom [u]	1985–1989	0.50		0.25	0.50									
	1990–1994													
United States [t]	1975–1979	3.96	1.73	7.19	1.82	4.16								
	1980–1984	3.92	1.44	3.07	0.78	2.12								
	1985–1989	4.25	1.66	2.07	0.49	1.24								
	1990–1994													
Total reported data [m]	1975–1979	4.50		7.38	1.62		0.00				0.12			
	1980–1984	4.93		3.73	0.76		0.00				0.26			
	1985–1989	5.72		3.52	0.62		0.01				0.19			
	1990–1994	1.31	0.58	0.98	0.75	1.68	0.00	0.01	0.04	0.19	0.03	0.09	0.42	0.83
All other industrial uses [c]														
Australia	1990–1994	2.90	1.14	0.58	0.20	0.60	0.00	0.00	0.00	0.04	0.29	0.31	0.48	0.77
Brazil	1990–1994	0.53	0.03	0.21	0.39	8.26	0.00	0.00	0.00	0.01	0.89	0.90	0.92	0.96
Bulgaria	1990–1994	0.14		0.14	1.04									
China	1990–1994	1.16	1.06	1.29	1.11	1.22	0.00	0.01	0.04	0.22	0.13	0.23	0.34	0.74
China, Taiwan Province	1990–1994	2.29	0.65	0.56	0.25	0.86								
Croatia	1990–1994	0.15	0.05	0.01	0.07	0.20								
Cuba	1991–1994	0.02	0.02	0.01	0.34	0.34	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Czech Republic	1991–1994	0.99	0.75	0.77	0.78	1.04	0.00	0.00	0.02	0.17	0.01	0.03	0.16	0.45
Denmark	1990–1994	2.37	0.30	0.12	0.05	0.42	0.00	0.00	0.00	0.01	0.06	0.06	0.23	0.48
Ecuador	1993–1994	0.03	0.03	0.06	2.63	2.63	0.02	0.04	0.08	0.84				

Table 22 (continued)

Country / area	Period	Monitored workers (thousands)	Measurably exposed workers (thousands)	Annual collective effective dose (man Sv)	Average annual effective dose (mSv)		Distribution ratio [b] (number of workers)				Distribution ratio (collective dose)			
					Monitored workers	Measurably exposed workers	NR_{15}	NR_{10}	NR_5	NR_1	SR_{15}	SR_{10}	SR_5	SR_1
Germany [h]	1990–1994	45.2	14.4	38.5	0.85	2.67	0.01	0.02	0.05	0.15	0.21	0.37	0.61	0.91
Hungary	1990–1994	1.38	0.04	0.05	0.04	1.16	0.00	0.00	0.00	0.01	0.11	0.11	0.25	0.66
Japan	1990–1994	60.7	3.29	7.52	0.12	2.29	0.00	0.00	0.01	0.02	0.27	0.37	0.55	0.88
Kuwait	1992–1994	0.03	0.00	0.01	0.11	0.4	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Mexico	1990–1994	0.30		0.27	0.91									
Netherlands	1990–1994	2.88	0.55	0.22	0.08	0.37	0.00	0.00	0.00	0.01	0.05	0.10	0.18	0.47
Norway	1990–1992	0.86	0.03	0.02	0.02	0.62	0.00	0.00	0.00	0.04				
Peru	1994	0.10	0.09	0.05	0.50	0.55	0.00	0.00	0.00	0.00				
Poland	1992–1994	0.93	0.84	0.89	0.96	1.01	0.00	0.00	0.01	0.63	0.00	0.01	0.03	0.80
Slovakia	1990–1994	0.35	0.07	0.09	0.26	1.36	0.00	0.00	0.00	0.09	0.06	0.06	0.08	0.77
Slovenia	1993–1994	0.71	0.48	0.19	0.27	0.40	0.00	0.00	0.00	0.02	0.07	0.07	0.07	0.15
Sri Lanka	1990–1994	0.01	0.00	0.01	0.83	2.46	0.02	0.03	0.06	0.08	0.48	0.67	0.89	0.91
Sweden	1990–1994	1.09		0.48	0.44									
Switzerland	1990–1994	2.77		0.33	0.12		0.00	0.00	0.01	0.02	0.18	0.29	0.56	0.88
Russian Federation	1992–1994	2.99	2.99	6.08	2.03		0.00				0.04			
United Kingdom	1990–1994	13.3	7.14	6.78	0.51	0.95	0.00	0.00	0.02	0.10				
Total reported data [m]	1990–1994	143	34.4	65.1	0.45	1.89	0.00	0.01	0.02	0.07	0.21	0.34	0.56	0.86

a Data are annual averages over the periods indicated.
b The values of NR are for the monitored workforce.
c Insufficient data are available for these categories to enable a reliable estimate of worldwide exposure.
d Reported data contain a contribution from industrial radiography.
e The total for measurably exposed workers has been rationed up to take account of countries that did not report the number of measurably exposed workers, but did report a figure for monitored workers.
f Reported data relate to approximately 25% of monitored workers.
g Reported data contain a contribution from industrial irradiation.
h Within the data from 1990–1994, the data concerning 1990 only relate to the Federal Republic of Germany. Earlier data is that combined from the German Democratic Republic and the Federal Republic of Germany.
i The reported data (covering about 80% of the workforce) have been scaled to represent the whole country.
j Data for 1980–1984 include only those workers whose dose records are held within the Dosemeter Issue and Record Keeping (DIRK) service of the NRPB. The total number of radiographers in the United Kingdom is somewhat larger. Data for 1985–1989 are for classified workers only.
k Reported data contain a contribution from other industrial uses (gauges).
l Calculation of SR distribution ratios based on data from 1993 and 1994.
m These data should be interpreted with care, particularly because the countries included in the summations for the representative five-year periods may not be the same, depending on whether data were reported for the period in question. Consequently, direct comparison of data for different periods is invalid to the extent that the data comprise contributions from different countries. It should also be noted that the data on NR_{15} and SR_{15} are averages of data reported on these ratios. In general, these data are less complete than those that form the basis of the summed number of workers and collective doses.
n These values are estimated by the method detailed in Section I.E.
o The doses include exposures from tritium intake and external radiation from promethium-147.
p All reported doses are from internal exposure only.
q Before 1989 radioisotope production was undertaken by Atomic Energy of Canada Limited, and separate statistics of this group of workers are not available. The average data tabulated for 1985–1989 are those for 1989, when production was transferred from Atomic Energy of Canada Limited; this accounts for the significant difference compared with the previous period. The contribution of internal exposure is small.
r Internal exposure included after 1986; it amounted to about 50%.
s Neutrons contribute about 15%–25% to the reported doses.
t Data are for licensees of the United States Department of Energy only. The effective doses include a neutron component.

Table 23
Reported exposures to workers from industrial uses of radiation (1990–1994) [a]

Region	Monitored workers	Measurably exposed workers [b]	Annual collective effective dose (man Sv)	Average annual effective dose (mSv)		Distribution ratio [c] (number of workers)				Distribution ratio (collective dose)			
				Monitored workers	Measurably exposed workers	NR_{15}	NR_{10}	NR_5	NR_1	SR_{15}	SR_{10}	SR_5	SR_1
Industrial irradiation													
East and South-East Asia	95	91	0.10	1.03	1.06	0.00	0.01	0.01	0.15	0.00	0.01	0.01	0.55
Eastern Europe	19	19	0.02	0.84	0.86	0.00	0.00	0.00	0.50	0.00	0.00	0.00	0.60
Indian subcontinent	15	9	0.00	0.09	0.15	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Latin America	64	56	0.07	1.09	1.25	0.00	0.01	0.01	0.31	0.06	0.13	0.13	0.68
OECD except United States	2 073	489	0.44	0.21	0.90	0.00	0.00	0.01	0.04	0.32	0.35	0.54	0.86
Remainder	11	3	0.01	0.42	1.40	0.00	0.00	0.00	0.09	0.00	0.00	0.00	0.64
Industrial radiography													
East and South-East Asia	7 418	3 697	6.15	0.83	1.66	0.01	0.02	0.04	0.14	0.36	0.48	0.60	0.80
Eastern Europe	3 937	2 390	6.02	1.53	2.52	0.01	0.02	0.07	0.39	0.14	0.25	0.44	0.87
Indian subcontinent	3 816	2 037	7.38	1.93	3.62	0.03	0.05	0.10	0.28	0.39	0.55	0.74	0.95
Latin America	1 483	733	1.98	1.34	2.70	0.01	0.02	0.05	0.25	0.28	0.35	0.52	0.87
OECD except United States	23 695	9 800	31.99	1.35	3.26	0.02	0.03	0.07	0.18	0.30	0.46	0.70	0.95
United States	5 599	3 746	18.31	3.27	5.68	0.03	0.10	0.20	0.42	0.29	0.60	0.82	0.98
Remainder	233	56	0.77	3.45	13.75	0.02	0.02	0.06	0.14	0.10	0.11	0.37	0.76
Luminizing													
East and South-East Asia	40	40	0.01	0.28	0.28	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
OECD except United States	23	10	0.01	0.54	1.17	0.00	0.00	0.00	0.18	0.00	0.00	0.00	0.73
Remainder	16	15	0.01	0.88	0.96	0.00	0.00	0.04	0.22	0.00	0.00	0.28	0.78
Radioisotope production													
East and South-East Asia	349	321	1.43	4.10	4.46	0.07	0.12	0.21	0.50	0.50	0.63	0.80	0.96
Eastern Europe	400	316	0.52	1.30	1.65	0.00	0.01	0.05	0.56	0.03	0.07	0.28	0.89
Indian subcontinent	548	390	0.77	1.41	1.97	0.01	0.03	0.07	0.29	0.22	0.32	0.51	0.85
Latin America	181	167	0.51	2.82	3.05	0.03	0.06	0.15	0.56	0.22	0.31	0.49	0.93
OECD except United States	1 831	1 281	3.91	2.14	3.05	0.02	0.06	0.18	0.46	0.15	0.33	0.67	0.95
United States	4 444	2 003	6.92	1.56	4.69	0.02	0.05	0.07	0.16	0.49	0.75	0.88	0.97
Remainder	136	87	0.30	2.21	3.45	0.03	0.07	0.12	0.37	0.24	0.61	0.73	0.94

Table 23 (continued)

Region	*Monitored workers*	*Measurably exposed workers* [b]	*Annual collective effective dose (man Sv)*	*Average annual effective dose (mSv)*		*Distribution ratio* [c] *(number of workers)*				*Distribution ratio (collective dose)*			
				Monitored workers	*Measurably exposed workers*	NR_{15}	NR_{10}	NR_5	NR_1	SR_{15}	SR_{10}	SR_5	SR_1
Well-logging													
East and South-East Asia	346	344	0.48	1.39	1.40	0.01	0.01	0.02	0.56	0.15	0.19	0.23	0.86
Eastern Europe	320	284	0.61	1.91	2.15	0.01	0.04	0.09	0.75	0.10	0.28	0.44	0.96
Indian subcontinent	874	510	0.45	0.51	0.87	0.00	0.00	0.01	0.15	0.02	0.05	0.15	0.65
Latin America	287	275	0.32	1.11	1.16	0.00	0.00	0.00	0.44	0.00	0.00	0.00	0.88
OECD except United States	6 492	2 449	1.18	0.18	0.48	0.00	0.00	0.00	0.05	0.08	0.11	0.30	0.85
Remainder	32	1	0.01	0.20	3.20	0.00	0.00	0.01	0.01	0.00	0.00	0.45	0.45
Accelerator operation													
East and South-East Asia	22	14	0.02	1.04	1.71	0.00	0.00	0.05	0.26	0.00	0.00	0.37	0.91
Eastern Europe	176	150	0.18	1.02	1.20	0.00	0.00	0.02	0.44	0.04	0.10	0.19	0.73
Latin America	31	18	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
OECD except United States	1 076	401	0.78	0.72	1.94	0.00	0.01	0.05	0.16	0.03	0.10	0.49	0.89
All medical uses													
East and South-East Asia	3 446	1 709	1.85	0.54	1.08	0.00	0.01	0.04	0.22	0.13	0.23	0.34	0.74
Eastern Europe	6 780	4 686	8.02	1.18	1.71	0.00	0.00	0.01	0.22	0.03	0.03	0.10	0.66
Indian subcontinent	13	4	0.1	0.83	2.46	0.02	0.03	0.06	0.08	0.48	0.67	0.89	0.91
Latin America	680	164	0.33	0.49	2.01	0.00	0.00	0.01	0.07	0.85	0.86	0.88	0.92
OECD except United States	132 345	27 122	54.83	0.41	1.98	0.00	0.01	0.02	0.07	0.22	0.37	0.60	0.90
Remainder	32	1	0.01	0.11	0.40	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

a Data are annual values averaged over the period reported.
b The values for measurably exposed workers has been rationed up to take account of countries that did not report the number of measurably exposed workers, but did report a figure for monitored workers.
c Insufficient data are available for these categories to enable a reliable estimate of worldwide exposure.

Table 24
Exposures to workers from all industrial uses of radiation [a]
Data from UNSCEAR Survey of Occupational Exposures

Country / area	*Period*	*Monitored workers (thousands)*	*Measurably exposed workers (thousands)*	*Annual collective effective dose (man Sv)*	*Average annual effective dose (mSv)*		NR_{15} [b]	SR_{15}
					Monitored workers	*Measurably exposed workers*		
Argentina	1985–1989	0.07	0.03	0.85	1.29	2.74	0.03	0.61
	1990–1994	0.53	0.28	0.68	1.27	2.44	0.01	0.25
Australia	1975–1979	2.21		0.92	0.41			
	1985–1989	7.1	3.30	0.78	0.11	0.23	0.00	0.09
	1990–1994	11.43	4.29	1.83	0.16	0.43	0.00	0.17
Brazil	1985–1989	15.00	3.10	24	1.60	7.69		
	1990–1994	1.44	0.43	1.47	1.02	3.40	0.01	0.40
Bulgaria	1990–1994	0.83	0.17	0.74	0.89	3.70	0.00	0.02
Canada	1975–1979	8.06	3.60	13.2	1.63	3.66	0.02	0.42
	1980–1984	11.0	4.36	14.4	1.31	3.30	0.02	0.34
	1985–1989	10.70	4.70	16.2	1.52	3.45	0.02	0.39
	1990–1994	4.59	2.52	9.84	2.14	3.91	0.03	0.34
China	1990–1994	4.76	4.25	6.8	1.43	1.60	0.01	0.24
China, Taiwan Province	1980–1984	2.42		1.91	0.79			
	1985–1989	3.04		1.97	0.65			
	1990–1994	4.67	1.74	1.47	0.31	0.85		
Croatia	1990–1994	0.26	1.00	0.07	0.27	0.88		
Cuba	1990–1994	0.33	0.33	0.41	1.25	1.25	0.00	0.02
Czech Republic	1975–1979	1.65		2.26	1.38		0.01	0.23
	1980–1984	2.92		3.77	1.29		0.01	0.18
	1985–1989	3.62		3.77	1.04		0.01	0.21
	1990–1994	2.33	1.81	2.85	1.22	1.58	0.00	0.06
Denmark	1975–1979	0.46		0.32	0.68		0.00	0.06
	1980–1984	0.64		0.49	0.76		0.00	0.11
	1985–1989	0.80		0.52	0.65		0.00	0.07
	1990–1994	2.76	0.50	0.52	0.19	1.04	0.00	0.04
Ecuador	1990–1994	0.17	0.15	0.25	1.49	1.72	0.00	
Finland [c]	1975–1979							
	1980–1984	0.67	0.05	0.14	0.21	2.97		0.20
	1985–1989	2.09	0.15	0.26	0.12	1.75	0.00	0.05
	1990–1994	2.36	0.17	0.32	0.14	1.94	0.00	0.06
		1.19	0.13	0.16	0.13	1.20	0.00	0.04
France	1975–1979							
	1980–1984							
	1985–1989	9.9		24	2.42			
Gabon	1990–1994	0.01	0.01	0.08	20.48	20.48	1.00	1.00
Germany [d]	1985–1989	58.6	14.70	25.6	0.44	1.74	0.01	0.29
	1990–1994	51.9	16.59	47.9	0.92	2.89	0.01	0.23
Greece	1990–1994	0.24	0.03	0.06	0.26	2.50	0.00	0.20
Hungary	1975–1979	3.26	0.58	3.01	0.92	5.14	0.01	0.36
	1980–1984	3.36	0.56	1.93	0.58	3.47	0.00	0.19
	1985–1989	3.26	0.53	1.57	0.48	2.97	0.00	0.12
	1990–1994	2.25	0.33	0.85	0.38	2.60	0.00	0.08

Table 24 (continued)

Country / area	*Period*	*Monitored workers (thousands)*	*Measurably exposed workers (thousands)*	*Annual collective effective dose (man Sv)*	*Average annual effective dose (mSv)*		NR_{15} [b]	SR_{15}
					Monitored workers	*Measurably exposed workers*		
Iceland	1990–1994	0.03	<0.01	0.00	0.00	0.00	0.00	
India	1990–1994	5.08	2.80	7.95	1.57	2.84	0.02	0.34
Indonesia	1980–1984	0.02	0.01	0.01	0.75	1.25		
	1985–1989	0.03	0.03	0.03	1.12	1.12		
Ireland	1985–1989	0.74	0.06	0.08	0.11	1.37	0.00	0.09
	1991–1994	0.13	0.23	0.03	0.23	1.32	0.00	
Italy [e]	1985–1989	1.98	0.44	0.87	0.44	1.97	0.00	0.35
Japan	1975–1979	27.6	3.93	8.93	0.32	2.27	0.01	
	1980–1984	29.0	4.06	11.0	0.38	2.70	0.00	
	1985–1989	32.00	3.06	8.48	0.27	2.77	0.00	
	1990–1994	120	6.49	16.5	0.14	2.54	0.00	0.31
Kuwait	1990–1994	0.19	0.03	0.62	3.26	22.96	0.00	0.00
Mexico	1985–1989	1.63	0.51	5.23	3.21	10.20	0.05	0.66
	1990–1994	1.69	0.51	5.2	3.07			
Myanmar	1990–1994	0.01	0.01	0.00	0.00	0.00	0.00	
Netherlands	1980–1984	1.71		0.63	0.37		0.00	0.34
	1985–1989	2.27		0.88	0.39		0.00	0.15
	1990–1994	4.09	1.38	2.68	0.65	1.95	0.01	0.19
New Zealand	1980–1984	0.28		0.43	1.50			
Norway	1980–1984	1.21	0.51	0.85	0.70	1.67	0.00	0.04
	1985–1989	1.44	0.51	0.68	0.47	1.35	0.00	0.09
	1990–1994	2.33	0.31	0.33	0.14	1.06	0.00	
Pakistan	1990–1994	0.13	0.12	0.62	4.66	5.00	0.11	0.63
Peru	1990–1994	0.26	0.23	0.4	1.54	1.75	0.01	
Poland	1990–1994	2.25	2.09	3.83	1.71	1.84	0.01	0.15
Portugal	1985–1989	0.63	0.52	0.18	0.28	0.34		
Russian Federation	1985–1989	12.8		104	8.15			
	1990–1994	2.99	2.99	6.08	2.03	2.03	0.00	0.04
Slovakia	1990–1994	0.89	0.36	0.91	1.03	2.50	0.00	0.10
Slovenia	1990–1994	0.81	0.58	0.3	0.37	0.52	0.00	0.10
South Africa	1975–1979	2.01	0.79	0.21	0.11	0.27	0.00	0.05
	1980–1984	2.90	1.18	2.11	2.11	5.17	0.03	0.41
	1985–1989	2.3	0.55	5.71	4.41	10.50	0.00	0.69
	1990–1994	0.12	0.08	0.27	2.31	3.60	0.03	0.27
Spain	1985–1989	3.02	2.0	3.98	1.32	1.60	0.01	0.02
Sri Lanka	1990–1994	0.06	0.03	0.04	0.73	1.54	0.01	0.49
Sweden	1990–1994	1.09		0.48	0.44			
Switzerland	1975–1979	11.7		10.2	0.87		0.01	0.31
	1980–1984	12.9		5.92	0.46		0.00	0.14
	1985–1989	13.6		4.08	0.30		0.00	0.08
	1990–1994	2.77		0.33	0.12		0.00	0.18
Syrian Arab Republic	1990–1994	0.07	0.01	0.02	0.28	2.50	0.00	0.00
Thailand	1990–1994	2.31	0.25	1.81	0.78	7.18	0.02	0.68

Table 24 (continued)

Country / area	*Period*	*Monitored workers (thousands)*	*Measurably exposed workers (thousands)*	*Annual collective effective dose (man Sv)*	*Average annual effective dose (mSv)*		NR_{15} [b]	SR_{15}
					Monitored workers	*Measurably exposed workers*		
USSR	1975–1979	7.78		126	16.2			
	1980–1984	9.85		122	12.4			
	1985–1989	12.8		104	8.15			
United Kingdom	1980–1984	28.0		26.0	0.93			
	1985–1989	18.80	15.1	21	1.12	1.39	0.01	
	1990–1994	19.60	10.27	13.0	0.67	1.27	0.00	
United Rep. Tanzania	1990–1994	0.03	0.02	0.08	2.46	3.56	0.00	0.00
United States [f]		202.00		290	1.44			
	1975–1979	305.00		380	1.25			
	1980–1984	274.00	101	150	0.55	1.49		
	1985–1989	10.04	5.75	25.2	2.51	4.39	0.03	0.34
Reported total [g]	1975–1979	240		445	1.81		0.01	0.36
	1980–1984	386		552	1.43		0.01	0.29
	1985–1989	423		343	0.81		0.01	0.34
	1990–1994	267	69	163	0.61	2.37	0.01	0.26
World estimate [h]	1975–1979	530	290	870	1.64	3.0	0.01	0.35
	1980–1984	690	300	940	1.36	3.2	0.01	0.28
	1989–1989	560	250	510	0.90	2.00	0.01	0.31
	1990–1994	700	160	360	0.51	2.24	0.00	0.25
		(390)	(100)	(240)	(0.62)	(2.34)	(0.01)	(0.26)

a Data are annual averages over the periods indicated.
b The values of NR are for the monitored workforce.
c Includes exposures of workers at the research reactor and in research establishments.
d Within the data from 1990-1994, the data concerning 1990 only relate to the Federal Republic of Germany.
e The reported number of workers is small compared with numbers in comparable industrialized countries, which suggests that the data are incomplete.
f Calculation of SR distribution ratios based on data from 1993 and 1994.
g The total for measurably exposed workers has been rationed up to take account of countries that did not report the number of measurably exposed workers, but did report a figure for monitored workers.
h The values shown in brackets are the world estimates based on the standard method given in Section I.E; however, the Committee identified a more robust method of estimation for this instance, based on the regional value for the United States being taken to be equivalent to the rest of the OECD (see para 156). These are the unbracketed figures.

Table 25
Summary of worldwide exposures from industrial uses of radiation [a]

Period	*Monitored workers (thousands)*	*Measurably exposed workers (thousands) [b]*	*Annual average collective effective dose (mSv)*	*Annual average individual dose (mSv)*	
				Monitored workers	*Measurably exposed workers*
Industrial radiography					
1985–1979	72		190	2.6	
1980–1984	120		230	2.0	
1985–1989	110		160	1.44	
1990–1994	106	53	170	1.58	3.17
Radioisotope production					
1985–1979	57		130	2.3	
1980–1984	82		100	1.3	
1985–1989	88		98	1.12	
1990–1994	24	26	47	1.93	2.95
Other [c d]					
1985–1979	260		480	1.8	
1980–1984	310		570	1.8	
1985–1989	200		230	1.1	
1990–1994	570		140	0.25	
All industry [d]					
1985–1979	390		800	2.05	
1980–1984	510		900	1.76	
1985–1989	400		490	1.23	
1990–1994 [e]	700 (390)	160 (100)	360 (240)	0.51 (0.62)	2.24 (2.34)

a The data are annual values averaged over the respective five year periods and are in general quoted to two significant figures.
b The total for measurably exposed workers has been rationed up to take account of countries that did not report the number of measurably exposed workers, but did report a figure for monitored workers.
c Estimated by subtracting the contributions from the specified practices from the estimated value for all industry.
d The “All industry” data in previous reports included “Tertiary education and research institutes”. The figures quoted in this document for the previous periods are with this component removed to permit a better comparison with the data for 1990–1994.
e The values shown in brackets are the world estimates based on the standard method given in Section I.E; however the Committee identified a more robust method of estimation for this instance, based on the regional value for the United States being taken to be equivalent to the rest of OECD (see para 156).

Table 26
Exposures to workers involved in industrial radiography in the United Kingdom
[H1, H2]

Year	*Numbers of workers in dose range*				*Total number of workers with dose > 5 mSv*	*Annual collective dose (man Sv)*	*Average annual dose (mSv)*	
	5–10 mSv	*10–15 mSv*	*15–20 mSv*	*>20 Sv*			*To all workers*	*To workers with non-zero doses*
1986	170	75	15	42	302	7.5	1.4	1.8
1987	125	52	24	25	226	6	1.0	1.5
1988	107	27	7	15	156	3.7	0.7	1.4
1989	89	39	18	24	170	4.8	0.8	1.9
1990	97	37	14	21	169	4.0	0.7	1.3
1991	120	32	26	24	202	4.6	0.9	1.7
1992	97	29	7	16	149	4.9	0.9	1.8
1993	79	23	8	18	128	3.0	0.6	1.5
1994	53	25	17	14	109	2.7	0.6	1.3
1995	56	12	5	11	84	2.4	0.6	1.4
1996	62	19	3	6	90	2.4	0.6	1.6

Table 27
Worldwide exposure from all industrial uses of radiation [a]

Region	*Monitored workers (thousands)*	*Measurably exposed workers (thousands)*	*Average annual collective dose (man Sv)*	*Average annual individual dose (mSv)*		*Collective effective dose [b] per unit GDP (man Sv per 10^{12} US$)*
				Monitored workers	*Measurably exposed workers*	
1975-1979						
East and South-East Asia [c]						
Eastern Europe [d]	17		176	10		150
Latin America						
OECD except United States [e]	210		240	1.1		79
United States (estimate)	200		290	1.4		150
Remainder [f]	100		170	1.7		120
Total	530		870	1.6		120
1980-1984						
East and South-East Asia	12		9	0.79		20
Eastern Europe [c]	20		150	7.9		68
Latin America						
OECD except United States [e]	240		240	0.99		49
United States (estimate)	310		380	1.3		110
Remainder [f]	110		160	1.4		73
Total	690		940	1.4		72
1985-1989						
East and South-East Asia [c]	10		7	0.65		13
Eastern Europe [d]	26		140	5.6		41
Latin America	24		43	1.8		52
OECD except United States [e]	180		130	0.69		16
United States (estimate)	270		150	0.55		31
Remainder [f]	41		35	0.85		26
Total	560		510	0.9		26
1990-1994						
East and South-East Asia	21	11	18	0.86	1.61	16
Eastern Europe	23	16	29	1.24	1.85	16
Indian subcontinent	7	4	12	1.64	2.92	24
Latin America	4	2	4	1.18	2.27	5
OECD except United States	320	62	140	0.44	2.27	12
United States [g]	320	62	140			
	(10)	(6)	(25)	(2.51)	(4.39)	(5)
Remainder	4	1	10	2.58	7.87	7
World [g]	700 (390)	161 (69)	510 (360)	0.51 (0.62)	2.24 (2.34)	34 (31)

a The data are annual averages over the respective five year periods and are, in general, quoted to two significant figures.
b The normalized collective doses per unit GDP for the three five year periods are expressed, respectively, in terms of 1977, 1983, 1989 and 1994 prices; direct comparison between the values for different periods is possible only after correcting for these different price bases.
c Non-centrally planned economies in East- and South-East Asia.
d Including the whole of the former USSR.
e All countries are members of the Organization for Economics Co-operation and Development (OECD) except for the United States.
f Includes the remainder of the world for which values are not specifically tabulated elsewhere in the Table. Note that the countries or regions comprising the remainder differ in the respective five year periods.
g The values shown in brackets are the world estimates based on the standard method given in Section I.E; however the Committee identified a more robust method of estimation for this instance, based on the regional value for the United States being taken to be equivalent to the rest of OECD (see para 156).

Table 28
Estimates of effective dose from cosmic radiation for typical flight routes
[E2]

Route	*Flight duration (min)*	*Effective dose (mSv)*	
		One flight on route	*1,000 hours flying on route*
Short-haul routes			
Dublin – Paris	95	0.0045	2.8
London– Rome	135	0.0067	3.0
Frankfurt – Helsinki	160	0.0100	3.7
Brussels – Athens	195	0.0098	3.0
Luxembourg – Madrid	130	0.0054	2.6
Stockholm – Vienna	140	0.0082	3.5
Lisbon – Munich	180	0.0091	3.0
Copenhagen – Dublin	120	0.0071	3.5
Amsterdam – Manchester	70	0.0030	2.6
Dublin – Rome	180	0.010	3.3
Long-haul routes			
Stockholm – Tokyo	605	0.051	5.0
Dublin – New York	450	0.046	6.1
Paris – Rio de Janeiro	675	0.026	2.3
Frankfurt – Bangkok	630	0.030	2.9
London – Toronto	490	0.050	6.2
Amsterdam – Vancouver	645	0.070	6.6
Los Angeles – Auckland	760	0.030	2.3
London – Johannesburg	655	0.025	2.3
Perth – Harare	665	0.039	3.5
Brussels – Singapore	675	0.030	2.7

Table 29
Reported exposures to workers from natural sources of radiation
Data from UNSCEAR Survey of Occupational Exposures

Country / area	*Period*	*Monitored workers (thousands)*	*Measurably exposed workers (thousands)*	*Annual collective effective dose (man Sv)*	*Average annual effective dose (mSv)*		*Distribution ratio (number of workers)*				*Distribution ratio (collective dose)*			
					Monitored workers	*Measurably exposed workers*	NR_{15}	NR_{10}	NR_5	NR_1	SR_{15}	SR_{10}	SR_5	SR_1
Civil aviation														
Bulgaria [a]	1990–1994	1.4		5.60	4.00									
Finland	1990–1994	1.93		3.78	1.96									
United Kingdom	1991	24.0		50.0	2.08									
Total	1990–1994	27.3		59.4	2.15									
Coal mining														
Myanmar	1994	< 0.01	< 0.01	0	0.68	0.68	0	0	0	0.50				
United Kingdom	1991	48.7		28.6	0.59									
Total	1990–1994	48.7		28.6	0.59		0	0	0	0.50				
Other mineral mining														
Australia	1990–1994	0.34	0.26	0.19	0.56	0.73	0	0	0	0.19	0	0.02	0.05	0.70
Finland	1990–1994	0.42		0.54	1.30									
Germany	1990–1994	1.02	1.00	2.35	2.31	2.19	0	0.01	0.09	0.71	0	0.04	.029	0.93
Slovenia [b]	1990–1994	0.18	0.18	6.38	34.7	34.7	0.79	0.84	0.91	0.99				
South Africa	1990–1994	250		640	2.6									
United Kingdom	1991	1.35		6.1	4.53									
Total	1990–1994	3.30		15.6	4.71		0.10	0.11	0.17	0.63	0	0.04	0.27	0.91
Oil and natural gas industries														
Myanmar	1990–1994	0.01	0.01	0	0.66	0.66	0	0	0	0.25				
United Kingdom	1990–1994	0.58	0.21	0.12	0.21	0.59	0	0	0.01	0.03				
Total	1990–1994	0.59		0.12	0.21		0	0	0.01	0.03				
Handling of minerals and ores														
South Africa	1990–1994	2.37	2.37	2.58	1.09	1.09	0	0	0.02	0.10	0	0.02	0.14	0.29

a Number of monitored workers is estimated. The assessment of dose is based on 400 flight hours and a mean dose rate. The radiation weighting factor for neutrons is taken to be 15.
b Reported data relate to workers in lead and zinc mines.

Table 30
Employment in underground mining worldwide in 1991
[C4]

Country	Number of miners (thousands)		
	Coal mining	Other mining	Total
China [a]	1 594	64	1 658
Czechoslovakia	55	2	57
Germany	105	4	109
India	669	10	679
Poland	251	10	261
South Africa	46	340	386
Spain	38	4	42
USSR	840	40	880
United Kingdom	46	2	48
United States	51	15	66
Other countries	213	265	478
Total	3 908	756	4 664

a The Chinese data for coal mining represent large and intermediate mines only, which produce about 60% of the coal.

Table 31
Exposures to radon and decay products in non-uranium mines

Country	Year	Coal mining			Other mining			Ref.
		Number of mines	Annual exposure (mSv)	Exposure above 10 mSv (%)	Number of mines	Annual exposure (mSv)	Exposure above 10 mSv (%)	
Australia	1991	3	1.0	0	23	0.5	0	[H10]
Canada	1980s				4	2.0	2	[A2]
France	1981	3	1.0	0	5	5.0	8	[B6]
Germany	1990	20	0.5	0				[R3]
	1991				45	7.0	18	[S6]
India	1980s	5	0.1	0				[M3]
	1980s				22	4.0	9	[N7]
Italy	1970s				35	6.0	8	[S7]
Poland	1980s	71	1.5	0.2	26	0.5	0	[D6]
South Africa	1970s				25	3.5	10	[G4]
	1993				40	1.8	0	[W4]
USSR		47	0.2		26	4.3		[P3]
United Kingdom	1980s	220	0.5	0				[D7]
	1990				41	2.3	7	[B7]
United States	1975	223	0.5	< 1	10	2.5	4	[R4]
	1990				99 [a]	6.0		[B8]
	1985				86 [b]	0.6		[E4]
Yugoslavia	1970s	5	1.0	0				[K3]
	1980s				2	8.5	50	[K3]

a Metal mines.
b Non-metal mines.

Table 32
Worldwide collective dose from inhalation of radon and its decay products from underground mining (excluding uranium) in the years 1990–1994

Country	*Number of miners* [a]	*Exposure to radon progeny* [b]	
		Annual collective effective dose (man Sv)	*Average annual effective dose (mSv)*
Coal mines			
Germany	105	53	0.50
India	669	67	0.10
Poland	251	380	1.50
USSR	840	170	0.20
United Kingdom	46	23	0.50
United States	51	26	0.50
Other	1 940	690	0.36
Total	3 910	1 410	0.36
Other mines (excluding uranium) [c]			
Germany	4	28	7.0
India	10	40	4.0
Poland	10	5	0.5
South Africa [d]	340	610	1.8
USSR	40	170	4.3
United Kingdom	2	5	2.3
United States	48 [e]	210	4.4
Other	306	750	2.4
Total [f]	760	1 820	2.4
All underground mines (excluding uranium mines)			
World	4 670	3 230	0.7

a Unless otherwise indicated, number of miners is taken from Table 30. In the category “Other mines” the number of miners also include uranium miners; corrections are made for this in the totals.
b Derived from reported exposures in Table 31 assuming a conversion factor of 5.0 mSv WLM^{-1}.
c The number of miners include those working in uranium mines and the estimated collective doses are, therefore, overestimates; this is corrected in the total collective dose but not on a country by country basis. The reported average individual doses are averages over all underground mines excluding coal and uranium mines.
d Exposure data taken from [W4] which are representative for the 1990s; somewhat higher levels were reported in the 1970s [G4] (see Table 31).
e Value taken from [E4]; it is for all underground miners in the United States except those working in coal and uranium mines.
f Uranium miners have been excluded from the total.

Table 33
Natural radionuclides in minerals and ores

Material	*Typical concentration in ore/raw material (kBq kg^{-1})*		*Typical concentration in tailings/wastes (kBq kg^{-1})*
	Uranium	*Thorium*	*^{226}Ra*
Bastnaesite		5	
Bauxite, red mud	<1	<1	<1
Fluorspar			4
Ilmenite and rutile	<1	<1	
Monazite	6–20	4% (by weight)	
Oil, natural gas			<4 000 (in scales in pipes)
Phosphate	0.1–4		<1 (in phosphogypsum wastes)
Pyrochlore and columbite	50	50	
Tin	<1	<1	
Zirconium (baddeleyite and zircon)	<5	<1	

Table 34
Minerals recovered in mining and processing of mineral sands in Western Australia
[K1]

Mineral	*Chemical formula*	*Percentage of production*	*Concentration (% by weight)* [a]	
			Thorium	*Uranium*
Ilmenite	$FeOTiO_2$	76	0.005–0.05	0.001–0.003
Monazite	$[Ce,La,Nd,Th]PO_4$	<1	5–7	0.1–0.5
Rutile	TiO_2	<5	0.005–0.01	0.001–0.003
Zircon	$ZrSiO_4$	19	0.01–0.025	0.015–0.03
Xenotine	YPO_4	<1	1.5	0.4

a 10^{-4}% (1 ppm) = 4.1 Bq kg^{-1} ^{232}Th and 12.5 Bq kg^{-1} ^{238}U. These data were erroneously converted and included in the UNSCEAR 1993 Report [U3].

Table 35
Summary of occupational exposures to natural radiation excluding uranium mining

Occupation or practice	*Number of workers (thousands)*	*Worldwide annual collective effective dose (man Sv)*	*Average annual effective dose (mSv)*
Coal mining [a]	3 910	2 600	0.7
Other mining [a]	760	2 000	2.7
Mineral processing, etc. [b]	300	300	1.0
Exposure above ground (radon) [c]	1 250	6 000	4.8
Aircrew	250	800	3.0
Total	6 500	11 700	1.8

a These estimates have been derived from the estimates for inhalation of radon and its progeny with corrections for the addition of 0.8 mSv per worker for naturally occurring external exposure and the reduction by 0.5 mSv per worker to account for the dose that the person would receive irrespective of work.
b Includes coal-fired power plants and extraction of mineral sands, phosphate ores and their subsequent use.
c A crude estimate extrapolated by GDP from an estimate of 240 man Sv in the United Kingdom arising from exposure inhalation of radon and its decay products in places of work above an action level.

Table 36
Exposures to workers in defence activities related to nuclear weapons in the United States
[D4]

Year	*Workers in workforce*	*Monitored workers*	*Measurably exposed workers*	*Average dose [a] (mSv)*	*Collective effective dose equivalent (man Sv)*			
					External photon	*External neutron*	*Internal*	*Total*
1990	177 313	108 065	36 074	0.85	18.5	3.8	8.2	30.5
1991	183 546	119 770	31 326	0.82	14.2	3.4	8.1	25.7
1992	191 036	123 711	29 414	0.78	11.9	3.1	7.9	23.0
1993	194 547	127 042	24 049	0.68	12.0	3.3	0.95	16.3
1994	184 073	116 511	25 390	0.65	12.7	3.3	0.43	16.4
1995	172 178	127 276	23 613	0.78	14.4	3.7	0.31	18.4

a To measurably exposed workers.

Table 37
Exposures to workers involved in defence activities in the United Kingdom
[H3, H9]

Year	*Number of workers*	*Percentage of workers in dose range*						*Average annual dose (mSv)*	*Annual collective dose (man Sv)*
		0–5 mSv	*5–10 mSv*	*10–15 mSv*	*15–20 mSv*	*20–30 mSv*	*>30 mSv*		
Nuclear weapons fabrication									
1990	3 935	98.9	0.9	0.1	0.00 [a]			0.4	1.7
1991	4 031	99.2	0.7	0.1	0.00 [a]			0.3	1.2
1992	4 153	99.2	0.8	0.00	0.00	0.00	0.00	0.3	1.1
1993	4 259	99.5	0.5	0.00	0.00	0.00	0.00	0.2	1.0
1994	4 320	99.9	0.1	0.00	0.00	0.00	0.00	0.2	0.8
Nuclear-powered ships and support facilities									
1990	8 516	92.8	4.8	1.5	0.5	0.4	0.01	1.3	11.1
1991	8 534	96.0	3.9	1.0	0.08	0.05	0.01	1.0	8.6
1992	10 861	97.8	1.97	0.16	0.00	0.018	0.028	0.7	7.3
1993	10 391	98.2	1.57	0.21	0.00	0.0	0.0	0.7	7.0
1994	10 596	99.1	0.75	0.16	0.00	0.0	0.0	0.6	6.2

a Above 15 mSv.

Table 38
Exposure to workers from defence activities [a]
Data from UNSCEAR Survey of Occupational Exposures

Country	Period	Monitored workers	Measurably exposed workers	Annual collective effective dose (man Sv)	Average annual effective dose (mSv)		Distribution ratio (number of workers)				Distribution ratio (collective dose)			
					Monitored workers	Measurably exposed workers	NR_{15}	NR_{10}	NR_5	NR_1	SR_{15}	SR_{10}	SR_5	SR_1
Weapons fabrication and associated activities														
United Kingdom [b]	1975–1979 [c]	3.14		2.95	0.94		0.00				0.00			
	1980–1984	3.71		3.56	0.96		0.00				0.00			
	1985–1989	4.20		2.46	0.59		0.00				0.00			
	1990–1994	4.14		1.16	0.28		0.00				0.00			
United States [d]	1975–1979	17.6	9.31	10.9	0.62									
	1980–1984	18.3	8.26	11.7	0.62									
	1985–1989	15.9	7.54	11.9	0.75									
	1990–1994	20.8	7.6	5.9	0.28									
Total [e]	1975–1979	20.8		13.8	0.67									
	1980–1984	22.5		15.2	0.68									
	1985–1989	20.1		14.4	0.71									
	1990–1994 [f]	24.9		7.1	0.28									
Nuclear ships and their support facilities														
United Kingdom [g]	1975–1979 [d]	6.36		26.3	4.13		0.071							
	1980–1984	6.43		20.1	3.11		0.050							
	1985–1989	6.24		11.6	1.86		0.019							
	1990–1994	9.78		8.0	0.82		0.00							
United States	1975–1979	35.2		65.9	1.87			0.051						
	1980–1984	45.3		45.8	1.01			0.012						
	1985–1989	56.4		45.6	0.81			0.012						
Total [e]	1975–1979	41.6		92.2	2.22									
	1980–1984	51.8		65.8	1.27									
	1985–1989	62.6		57.3	0.91									
	1990–1994	9.8		8.0	0.82									

Table 38 (continued)

Country	Period	Monitored workers	Measurably exposed workers	Annual collective effective dose (man Sv)	Average annual effective dose (mSv)		Distribution ratio (number of workers)				Distribution ratio (collective dose)			
					Monitored workers	Measurably exposed workers	NR_{15}	NR_{10}	NR_5	NR_1	SR_{15}	SR_{10}	SR_5	SR_1
All defence activities														
France	1990–1994	5.7	0.73	1.31	0.23	1.78	0.00	0.00	0.01	0.13				
Netherlands	1990–1994	0.15	0.02	<0.01	0.01	0.19	0.00	0.00	0.00	0.00	0.00	0.00	0.00	
United Kingdom	1975–1979	11.9		35.8	3.00		0.04							
	1980–1984	12.8		26.3	2.06		0.03							
	1985–1989	12.2		14.6	1.19		0.01							
	1990–1994	13.9		9.2	0.66		0.00	0.00	0.02					
United States	1975–1979	92.5	55.8	101	1.09	1.81								
	1980–1984	104	61.5	56	0.54	0.91								
	1985–1989	115	73.0	69	0.60	0.95								
	1990–1994	119	29.3	22	0.19	0.76								
Total	1975–1979	104		137	1.3									
	1980–1984	116		82	0.71									
	1985–1989	127		84	0.66									
	1990–1994	139		33	0.24									

a The data are annual values over the indicated periods.
b The actual effective doses are typically less than 50% of the tabulated values, which are those measured by the dosimeter.
c The value for this period are averages for the year 1979.
d Includes exposures of employees of the United States Department of Energy and contractors engaged in weapons fabrication and testing. Before 1987 the collective doses were evaluated as the sum of the products of the number of workers and the mean dose in dose interval; subsequently, actual individual doses were used in the summation.
e Values derived as the sum or weighted average of the five-year averaged data for the United Kingdom and the United States.
f The value used is the average for 1992-1994, taken from [D4].
g The data are reported for on-board and shore personnel. Shore-based personnel may compromise both civilian and service personnel. Since the early 1980s, dosimeters have been issued only to on-board personnel who need it during their duties at sea and to those designated as classified persons on shore.

Table 39
Exposures to workers from miscellaneous uses of radiation [a]
Data from UNSCEAR Survey of Occupational Exposures

Country	Period	Monitored workers (thousands)	Measurably exposed workers (thousands)	Annual collective effective dose (man Sv)	Average annual effective dose (mSv)		Distribution ratio [b] (number of workers)				Distribution ratio (collective dose)			
					Monitored workers	Measurably exposed workers	NR_{15}	NR_{10}	NR_5	NR_1	SR_{15}	SR_{10}	SR_5	SR_1
Educational establishments														
Australia [c d]	1975–1979	0.55		0.055	0.10									
	1985–1989	2.22	0.94	0.069	0.03	0.07	0.00				0.00			
	1990–1994	0.62	0.21	0.02	0.04	0.11	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.23
Brazil [e]	1990–1994	0.94	0.04	0.02	0.03	0.54	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.42
Bulgaria [f]	1992	0.25		0.25	1.00									
Canada [g]	1975–1979	5.01	0.89	0.69	0.14	0.78	0.0005				0.090			
	1980–1984	7.40	1.02	0.80	0.11	0.78	0.0003				0.044			
	1985–1989	9.51	1.62	1.05	0.11	0.65	0.0003				0.086			
	1990–1994	14.7	1.51	0.76	0.05	0.50	0.00	0.00	0.00	0.01	0.03	0.06	0.14	0.44
China, Taiwan Province	1985–1989	0.71		0.04	0.056									
	1990–1994	1.10	0.22	0.15	0.14	0.69	0.00	0.00	0.00	0.02	0.18	0.18	0.23	0.47
Cuba	1990–1994	0.02	0.02	0.03	1.32	1.34	0.00	0.00	0.00	0.50	0.00	0.00	0.00	0.31
Czech Republic [h]	1975–1979	0.08		0.04	0.45		0.003				0.23			
	1980–1984	0.18		0.18	0.97		0.017				0.58			
	1985–1989	0.21		0.12	0.56		0.001				0.030			
	1990–1994	0.86	0.60	0.57	0.66	0.93	0.00	0.00	0.01	0.16	0.04	0.06	0.13	0.46
Finland [i]	1980–1984	0.95	0.023	0.038	0.040	1.63	0.00				0.062			
	1985–1989	1.18	0.032	0.053	0.045	1.68	0.008				0.11			
	1990–1994	1.33	0.08	0.22	0.17	2.79	0.00	0.00	0.01	0.03	0.21	0.42	0.64	0.92
France	1985–1989	3.8	0.09	0.20	0.053	2.22	0.001							
Germany [j k l]	1975–1979	0.22	0.008	0.022	0.104	2.79	0.0009				0.19			
	1980–1984	0.21	0.003	0.003	0.015	0.93	0.00				0.00			
	1985–1989	21.31	1.055	1.539	0.116	3.48	0.0004				0.17			
	1990–1994	26.6	0.90	0.88	0.03	0.98	0.00	0.00	0.00	0.01	0.08	0.14	0.30	0.70
Greece	1990–1994	0.35	0.02	0.02	0.06	1.19	0.00	0.00	0.00	0.02	0.00	0.00	0.22	0.73

Table 39 (continued)

Country	Period	Monitored workers (thousands)	Measurably exposed workers (thousands)	Annual collective effective dose (man Sv)	Average annual effective dose (mSv)		Distribution ratio [b] (number of workers)				Distribution ratio (collective dose)			
					Monitored workers	Measurably exposed workers	NR_{15}	NR_{10}	NR_5	NR_1	SR_{15}	SR_{10}	SR_5	SR_1
Hungary [m]	1975–1979	0.22	0.008	0.022	0.104	2.79	0.0009				0.19			
	1980–1984	0.21	0.003	0.003	0.015	0.93	0.00				0.00			
	1985–1989	0.21	0.005	0.009	0.044	2.02	0.00				0.00			
	1990–1994	0.39	0.01	0.01	0.04	0.95	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.62
India [n]	1980–1984	1.01	0.17	0.29	0.29	1.74	0.003				0.24			
	1985–1989	1.92	0.47	0.45	0.24	0.97	0.0005				0.067			
	1990–1994	2.06	0.54	0.44	0.21	0.81	0.00	0.00	0.00	0.05	0.07	0.09	0.16	0.59
Indonesia	1980–1984	0.28	0.19	0.25	0.92	1.33	0.018				0.37			
	1985–1989	0.66	0.64	0.48	0.72	0.75	0.003				0.11			
Italy	1985–1989	0.66	0.085	0.054	0.082	0.634	0.003				0.001			
Japan	1980–1984	21.4	0.79	0.49	0.023	0.62	0.0002							
	1985–1989	27.6	0.69	0.46	0.017	0.67	0.0000							
	1990–1994	59.2	0.86	0.86	0.01	1.01	0.00	0.00	0.00	0.00	0.20	0.28	0.40	0.73
Myanmar	1990–1994	0.02	0.02	0.02	1.18	1.18	0.00	0.03	0.04	0.23				
Netherlands	1990–1994	2.10	0.29	0.31	0.15	1.02	0.00	0.00	0.01	0.01	0.52	0.66	0.73	0.82
Norway [o]	1980–1984	0.42	0.025	0.014	0.032	0.55	0.00				0.00			
	1985–1989	0.45	0.029	0.026	0.057	0.90	0.001				0.48			
	1990–1992	0.56	0.09	0.02	0.04	0.24	0.00	0.00	0.00	0.01				
Pakistan	1990–1994	0.03	0.02	0.07	2.73	2.94	0.02	0.08	0.18	0.31	0.25	0.52	0.83	0.91
Portugal	1985–1989	0.78	0.37	0.33	0.42	0.88								
Slovakia	1990–1994	0.31	0.12	0.10	0.33	0.96	0.00	0.00	0.00	0.10	0.00	0.00	0.11	0.49
South Africa	1975–1979	0.23	0.042	0.002	0.007	0.04	0.00				0.00			
	1980–1984	0.36	0.091	0.47	1.29	5.12	0.020				0.45			
	1985–1989	0.43	0.070	0.21	0.49	3.02	0.00				0.10			
Sri Lanka	1990–1994	0.03	0.03	0.00	0.05	0.53	0.00	0.00	0.00	0.02	0.00	0.00	0.00	0.70
Sweden	1990–1994	2.38		0.12	0.05									
Switzerland [p]	1975–1979	7.44		5.91	0.79		0.007							
	1980–1984	8.48		3.44	0.41		0.0006							
	1985–1989	8.83		2.88	0.33		0.0003							
	1990–1994	9.44		2.17	0.23		0.00	0.00	0.01	0.05	0.02	0.06	0.22	0.61

Table 39 (continued)

Country	Period	Monitored workers (thousands)	Measurably exposed workers (thousands)	Annual collective effective dose (man Sv)	Average annual effective dose (mSv)		Distribution ratio [b] (number of workers)				Distribution ratio (collective dose)			
					Monitored workers	Measurably exposed workers	NR_{15}	NR_{10}	NR_5	NR_1	SR_{15}	SR_{10}	SR_5	SR_1
Syrian Arab Republic	1990–1994	0.23	0.03	0.05	0.20	0.96	0.00	0.00	0.00	0.02	0.00	0.00	0.05	0.45
Thailand	1990–1994	0.56	0.07	0.07	0.12	0.92	0.00	0.00	0.01	0.02	0.25	0.33	0.52	0.85
United Kingdom	1980–1984 1985–1989 1990–1994	12.5 1.17 1.26	 0.49 0.32	1.3 0.38 0.21	0.10 0.32 0.17	 0.78 0.67	0.00 0.002 0.00	 0.00	 0.01	 0.02	0.00			
United Rep. Tanzania	1990–1994	0.02	0.02	0.04	2.14	2.69	0.00	0.00	0.19	0.42	0.00	0.00	0.54	0.87
United States [q]	1975–1979 1980–1984 1985–1989	0.02 0.03 0.02		18 15 6	0.72 0.58 0.35	 0.86								
Total [r]	1975–1979 1980–1984 1985–1989 1990–1994	38.6 66.0 85.7 125.4	 6.58	23.5 20.4 13.6 7.41	0.61 0.31 0.16 0.06	 1.13	0.004 0.0007 0.0004 0.00	 0.00	 0.00	 0.01	0.19 0.11 0.072 0.09	 0.15	 0.28	 0.62
World [s]	1975–1979 1980–1984 1985–1989 1990–1994	140 180 160 310	 30.0	74 43 22 33	0.55 0.24 0.14 0.11	 1.10	 0.00	 0.00	 0.00	 0.02	 0.07	 0.11	 0.22	 0.55
Veterinary medicine														
Australia [c d]	1975–1979 1985–1989 1990–1994	0.39 2.07 2.66	 0.89 0.88	0.055 0.02 0.07	0.14 0.01 0.03	 0.02 0.07	0.00 0.00 0.00	 0.00	 0.00	 0.00	0.00 0.00 0.16	 0.16	 0.16	 0.30
Brazil [e]	1990–1994	0.02	0.003	0.00	0.25	1.39	0.00	0.00	0.00	0.08	0.00	0.00	0.00	0.78
Canada	1975–1979 1980–1984 1985–1989 1990–1994	0.77 1.27 1.52 2.14	0.24 0.22 0.31 0.29	0.17 0.16 0.17 0.13	0.22 0.13 0.11 0.06	0.73 0.74 0.56 0.46	0.0008 0.0002 0.00	 0.00	 0.00	 0.01	0.11 0.026 0.00	 0.02	 0.05	 0.38
Cyprus	1990–1994	0.002	0.002	0.00	0.70	0.88	0.00	0.00	0.00	0.30	0.00	0.00	0.00	0.87
Czech Republic [h]	1975–1979 1980–1984 1985–1989 1990–1994	0.17 0.23 0.25 0.23	 0.18	0.10 0.14 0.13 0.18	0.59 0.62 0.52 0.75	 0.97	 0.00	 0.00	 0.00	 0.17	 0.00	 0.00	 0.00	 0.37

Table 39 (continued)

Country	*Period*	*Monitored workers (thousands)*	*Measurably exposed workers (thousands)*	*Annual collective effective dose (man Sv)*	*Average annual effective dose (mSv)*		*Distribution ratio* [b] *(number of workers)*				*Distribution ratio (collective dose)*			
					Monitored workers	*Measurably exposed workers*	NR_{15}	NR_{10}	NR_5	NR_1	SR_{15}	SR_{10}	SR_5	SR_1
Denmark	1975–1979	0.49		0.022	0.045		0.00				0.00			
	1980–1984	0.52		0.030	0.059		0.0004				0.17			
	1985–1989	0.71		0.024	0.034									
	1990–1994	0.94	0.06	0.02	0.02	0.37	0.00	0.00	0.00	0.00	0.00	0.00	0.09	0.55
Finland	1980–1984		0.010	0.012		1.20					0.00			
	1985–1989		0.02	0.03		1.20								
	1990–1994	0.19	0.04	0.06	0.29	1.50	0.00	0.00	0.01	0.09	0.00	0.00	0.30	0.84
France [t]	1985–1989	1.19	0.09	0.02	0.17	2.30	0.00							
Hungary	1975–1979	0.081	0.009	0.045	0.55	5.07	0.010				0.42			
	1980–1984	0.14	0.01	0.03	0.20	2.78	0.00				0.24			
	1985–1989	0.06	0.004	0.01	0.10	1.56	0.00	0.00	0.00	0.03	0.00	0.00	0.16	0.74
	1990–1994													
Iceland	1990–1994	0.01	0.00		0.00		0.00	0.00	0.00	0.00				
India	1975–1979	0.062	0.021	0.011	0.17	0.51	0.00				0.00			
	1980–1984	0.080	0.026	0.16	0.20	0.61	0.00				0.00			
	1985–1989	0.09	0.03	0.02	0.20	0.53	0.00				0.20			
Ireland	1985–1989	0.04	0.002	0.00	0.02	0.33								
Japan [u]	1985–1989	18.0		1.4	0.08									
	1990–1994	1.38	0.20	0.15	0.11	0.71	0.00	0.00	0.00	0.02				
Myanmar	1990–1994	0.004	0.004	0.00	0.61	0.61	0.00	0.00	0.00	0.00				
Netherlands	1990–1993	1.16	0.57	0.53	0.45	0.92	0.00	0.01	0.02	0.12	0.14	0.25	0.42	0.77
Slovakia	1990–1994	0.08	0.01	0.01	0.14	1.14	0.00	0.00	0.00	0.04	0.00	0.00	0.00	0.61
Slovenia	1990–1994	0.008	0.008	0.01	0.76	0.76	0.00	0.00	0.00	0.05				
South Africa	1975–1979	0.42	0.28	0.013	0.032	0.048	0.001				0.42			
	1980–1984	0.61	0.20	0.12	0.20	0.60	0.001				0.056			
	1985–1989	0.75	0.13	0.24	0.32	1.89	0.001				0.068			
	1990–1994	0.75	0.13	0.24	0.32	0.89	0.00				0.07			
Sweden	1992–1994	0.68		0.08	0.12									

Table 39 (continued)

Country	Period	Monitored workers (thousands)	Measurably exposed workers (thousands)	Annual collective effective dose (man Sv)	Average annual effective dose (mSv)		Distribution ratio [b] (number of workers)				Distribution ratio (collective dose)			
					Monitored workers	Measurably exposed workers	NR_{15}	NR_{10}	NR_5	NR_1	SR_{15}	SR_{10}	SR_5	SR_1
Switzerland	1975–1979	0.44		0.12	0.27		0.0006				0.032			
	1980–1984	0.59		0.13	0.22		0.00				0.00			
	1985–1989	1.03		0.05	0.05									
	1990–1994	1.39		0.07	0.05		0.00	0.00	0.00	0.01	0.00	0.00	0.11	0.56
United Kingdom	1985–1989	4.00		0.4	0.1									
	1990–1994	0.30	0.08	0.02	0.06	0.21	0.00	0.00	0.00	0.00				
United States [v]	1975–1979	18.1	6.2	14	0.77	2.26								
	1980–1984	21	12	13	0.62	1.08								
	1985–1989	85.0	38.0	36	0.42	0.95								
	1990–1994													
Total reported data [r]	1975–1979	19.7		14.4	0.73		0.001				0.12			
	1980–1984	23.8		13.5	0.57		0.0002				0.027			
	1985–1989	96.4		37.1	0.39		0.00				0.02			
	1990–1994	11.26	2.84	1.34	0.12	0.47	0.00	0.00	0.00	0.03	0.08	0.13	0.24	0.60
World [s]	1975–1979	48		25	0.52									
	1980–1984	65		26	0.40									
	1985–1989	160.0		52	0.32									
	1990–1994	45.0	13.0	8	0.18	0.62	0.00	0.00	0.00	0.03	0.02	0.13	0.24	0.60
Other occupational groups														
Brazil [e]	1990–1994	0.39	0.06	0.30	0.78	4.96	0.01	0.01	0.02	0.06	0.72	0.76	0.84	0.95
China, Taiwan Province	1990–1994	1.99	0.68	1.02	0.51	1.49								
Cuba	1991–1994	0.16	0.15	0.12	0.74	0.74	0.00	0.00	0.00	0.23	0.00	0.00	0.01	0.48
Cyprus	1990–1994	0.01	0.009	0.01	0.61	0.94	0.00	0.00	0.00	0.25	0.00	0.00	0.00	0.77
Czech Republic	1991–1994	0.66	0.47	0.47	0.71	1.00	0.00	0.01	0.02	0.13	0.04	0.13	0.30	0.58
Denmark	1990–1994	0.19	0.002	0.00	0.00	0.00	0.00	0.00	0.00	0.00				
Ecuador	1993–1994	0.05	0.05	0.06	1.04	1.05	0.00	0.00	0.00	0.50				
France	1990–1994	0.84	0.54	3.46	4.10	6.36	0.07	0.13	0.28	0.64				
Germany [j]	1990–1994	3.63	1.14	2.32	0.64	2.03	0.00	0.01	0.03	0.16	0.12	0.21	0.44	0.90
Greece	1990–1994	0.25	0.03	0.07	0.29	2.42	0.00	0.00	0.1	0.06	0.27	0.34	0.53	0.89
Netherlands	1990–1993	0.25	0.01	0.02	0.09	1.84	0.00	0.00	0.00	0.01	0.71	0.71	0.71	0.88
Peru	1994	0.04	0.04	0.02	0.60	0.60	0.00	0.00	0.00	0.23				
Slovakia	1990–1994	0.25	0.12	0.14	0.57	1.18	0.00	0.00	0.00	0.18	0.00	0.00	0.01	0.67
Slovenia	1990–1994	0.06	0.06	1.15	17.7	17.7	0.60	0.75	0.91	0.94	0.88	0.99	1.00	1.00
United States	1990–1994	0.58	0.14	0.40	0.70	0.95	0.00	0.02	0.04	0.12	0.17	0.52	0.77	0.95
Total	1990–1994	9.37		9.56	1.03		0.02	0.03	0.06	0.20	0.33	0.42	0.57	0.88

Table 39 (continued)

a The data are annual values averaged over the indicated periods. They were derived as averages over the years for which data were reported; in some cases, data were reported for only a limited number of years in the periods of interest here.
b The values of NR_{15} are now for the monitored workforce. Values for the exposed workforce can also be estimated where data are given for both monitored and measurably exposed workers.
c For 1975–1989; numbers of workers and the collective doses reported in questionnaire for about 70% of the exposed workforce have been extrapolated for entire country.
d The method of dose recording was different in the two periods for which data are reported, and this may partly account for the differences in data. Average individual doses for 1975–1979 were calculated from the total of the reported doses for an occupational category divided by the estimated number of workers in that category with the results rounded to the nearest 0.1 mSv. In 1990 the estimates were based directly on the results of individual monitoring; in the absence of data for 1985–1989, the data for 1990 have been assumed to be representative of this period.
e Reported data are based on a sample of approximately 25% of monitored workers.
f Reported data contain a contribution from veterinary medicine.
g Data are mainly from universities but exclude exposures at accelerators and in teaching establishments where little research is undertaken.
h Data for 1975–1989 relate to the former Czechoslovakia.
i Includes all research institutes except research reactors and accelerators. No data are available on exposures in tertiary education.
j Within the data from 1990–1994, the data concerning 1990 only relate to Federal Republic of Germany.
k For 1976–1980, the data are for all universities and technical colleges in the non–medical field. For 1981–1989, the data are for all research and education except for that associated with medical and nuclear sciences.
l Data include exposures arising in research and training in natural sciences and technology, including research centres.
m Includes technological education only (i.e. not medicine, science, philosophy etc).
n Includes data from education and research institutes.
o 1980–1989 data are solely for the University of Oslo.
p Data may include some data on research for the nuclear fuel cycle.
q Data are for licensees of the United States Nuclear Regulatory Commission only.
r These data should be interpreted with care, particularly because the countries included in the summations for the respective five–year periods may not be the same, depending on whether data were reported for the period in question. Consequently, direct comparisons of data for different periods is invalid to the extent that the data comprise contributions from different countries. It should also be noted that the data on NR and SR are averages of data reported on these ratios. In general, these data are less complete than those that form the basis of number of workers and collective doses.
s The estimates are extrapolations of regional values based on the gross national product (GDP); because of insufficient data, the estimates of NR and SR are averages of reported data, but these may be considered representative for worldwide exposure.
t The number of workers and the collective dose have been scaled up by a factor of 1.33, since the reported data only covered 75% of those monitored.
u For 1985–1989 the data is for holding assistants; 1.06 man Sv of the collective dose arose in radiographic examinations and 0.34 man Sv in fluoroscopy. Some 2.4 million radiographs were taken with about 5% on large animals with remainder on small animals.
v The values for 1985 (the period 1985–1989) are based on extrapolation of earlier data.

Table 40
Accidents with clinical consequences to occupationally exposed workers
Data from UNSCEAR Survey of Occupational Exposures unless otherwise specified

Country / location	*Year of accident*	*Type of installation or operation*	*Main cause of exposure*	*Persons affected*	*Nature of exposure and health consequences*
Nuclear fuel cycle					
Argentina Atucha	1977	Nuclear reactor	Worker not wearing lead gloves; contamination of a cut caused by edge of the manway plug	1	Wound contaminated with 3,800 Bq (surgical removal of a contaminant); mean beta dose 364 Gy in period 1977–1985 and annual gamma dose of 0.04 in 1 cm^3 of soft tissue; no deterministic effects observed
Argentina Buenos Aires	1983	Critical facility	Failure to follow procedures in removing water from tank containing fissile material	1	Acute whole-body dose of 43 Gy (23 Gy neutron and 21 Gy gamma); death by acute radiation syndrome (neurological) with radiopneumonitis in right lung
France [a]	1979	Nuclear power plant		1	Whole-body dose of 0.34 Gy
German Democratic Rep. Rossendorf	1975	Research reactor	Neutron activation of a sample grossly underestimated	1	Dose of 20–30 Gy to right hand; acute and chronic radiodermatitis (2nd and 3rd degree) and oedema
Hungary Paks	1989	Reactor maintenance	Careless handling of detectors from reactor vessel	1	Whole-body dose of 29 mGy; 1 Gy to fingers on the left hand; temporary increase in temperature in left hand; slight increase in chromosomal aberrations
Sweden Nykoping	1978	Research reactor	Instructions for work not followed	1	Dose of 30 Gy to skin of hand; radiation burn to skin
USSR Chernobyl	1986	Reactor accident	Breach of operating rules	237	Whole-body doses of 1–16 Gy and localized doses to skin; 30 deaths; medical treatment including bone marrow transplants
United States Hanford	1976		Intake of ^{241}Am	1	Dose to bone of 8.6 Gy
United Kingdom [b]	1976		Contamination of both hands and feet from mainly beta-emitting radionuclides	1	Skin dose estimated to be about 1.5 Gy; no clinical effects reported
Industrial uses of radiation					
Argentina La Plata, B.A.	1977	X-ray crystallography	Shutter removed from crystallography set	3	Dose of 10 Gy to hands of one operator (radiation burns); doses to other not quoted
Argentina Buenos Aires	1978	^{192}Ir industrial source	Manual handling of source	1	Dose of 12–16 Gy causing radiation burns to two fingers on left hand
Argentina Buenos Aires	1981	^{192}Ir industrial source	Source became detached and lodged in the delivery tube	2	Doses not quoted; radiation burns on finger tips
Argentina Mendoza	1984	^{192}Ir industrial source	Operator pushed source into camera using a finger	1	Dose of 18 Gy to finger (radiation burn on finger) and of 0.l1 Gy to the whole body

Table 40 (continued)

Country / location	*Year of accident*	*Type of installation or operation*	*Main cause of exposure*	*Persons affected*	*Nature of exposure and health consequences*
Bangladesh [a]	1989	^{192}Ir industrial source		1	Whole-body dose of 2.3 Gy
Belarus Nesvizh	1991	^{60}Co irradiation facility	Improper entry with source exposed	1	11 Gy whole body; death in 113 days
China [c] Shanghai	1980	^{60}Co irradiation facility	Entry into the irradiation chamber during power failure and with defective interlocks	1	Whole-body dose of 5 Gy and localized exposure
China Kaifeng City	1986	^{60}Co source	Accidental exposure for about 3 minutes	2	Whole-body doses of 2.6 and 3.5 Gy; haemopoietic type of acute radiation sickness
China Zhengzhou City	1987	^{60}Co irradiation facility	Accidental entry to irradiation room for 10–15 seconds	1	Estimated whole-body dose of 1.35 Gy; anorexia and nausea four hours later; severe damage to haemopoietic system with restoration of WBC was relatively slow
China Zhao Xian	1988	^{60}Co irradiation facility	Accidental entry to irradiation room for about 40 seconds	1	Estimated whole-body dose of 5.2 Gy; acute radiation sickness (bone marrow syndrome); after three years follow-up, condition good
China Beijing	1989	^{60}Co source	Accidental exposure to source for about 4 minutes	2	Whole-body doses of 0.87 and 0.61 Gy; both suffered mild haemopoietic radiation sickness; recovered
China [c]	1989	^{192}Ir radiography source		1	Localized exposure of 18.37 Gy
China Shanghai	1990		Entry into the irradiation chamber during power failure and with defective interlocks	7	The workers received between 2 and 12 Gy: the two who received 11 and 12 Gy died
China	1992	Irradiation facility	Power loss and safety interlocks out of order	4	1 worker with acute radiation syndrome
Czechoslovakia Pardubice	1977	^{192}Ir industrial radiography source	Technical failure of the equipment and improper actions to bring source back under control	1	Whole-body dose of about 5 mSv; data insufficient for estimating local doses; bullous dermatitis of the thumb of the right hand; plastic surgery two years later
Czechoslovakia Sokolov	1979	^{192}Ir industrial radiography source	Technical failure of the equipment and inadequate monitoring during and after work	1	Whole-body dose of about 5 mSv; data insufficient for estimating local doses; bullous dermatitis of the third finger of the left hand and adjacent areas; plastic surgery two years later
Czechoslovakia Prague	1982	^{192}Ir industrial radiography source	Source transport container declared empty on delivery from abroad and handled as if inactive	1	Whole-body dose of about 2 mSv; data insufficient for estimating local doses; bullous dermatitis of thumb of right hand; conservative treatment
Czechoslovakia Petrvald	1985	Dilution, using a needle, of ^{241}Am solution in glove box	Carelessness and inadequate equipment for work with transuranics	1	Intake through wound of 600 Bq of ^{241}Am; surgical excision of wound and administration of DTPA
Czechoslovakia Prague	1988	Manufacturing of foils containing ^{241}Am for use in fire alarms	New rolling method not tested inactively first; poor radiation protection practice	1	Inhalation of 50 kBq of dispersed ^{241}Am; hospitalization and administration of DTPA; no clinical manifestations

Table 40 (continued)

Country / location	*Year of accident*	*Type of installation or operation*	*Main cause of exposure*	*Persons affected*	*Nature of exposure and health consequences*
El Salvador [a]	1989	^{60}Co irradiation facility	Deterioration of safety system and lack of understanding of radiation hazards	3	Whole-body dose of 3–8 Gy; 1 death
France [c] Nancy	1978	X-ray equipment		1	Localized exposure of hand; amputation of finger
France [c] Montpelier	1979	^{192}Ir radiography source		1	Whole-body and localized exposure; amputation of left arm
France Forbach	1991	Irradiation facility	Exposure to accelerator dark current	3	Severe skin lesions to one worker; less serious injury to two others
German Democratic Rep. Freiberg	1979	X-ray fluorescence unit	Carelessness	1	Dose of 10–30 Gy to right hand and whole-body dose of 0.2–0.5 Gy; acute and chronic radiodermatitis (2nd and 3rd degree)
German Democratic Rep. Bohlen	1980	Analytical x-ray unit	Carelessness	1	Dose of 15–30 Sv to left hand; acute and chronic radiodermatitis (2nd and 3rd degree)
German Democratic Rep. Schwarze Pumpe	1983	^{192}Ir industrial source	Technical defect and inappropriate handling	1	Dose to the right hand of about 5 Gy; acute and chronic radiodermatitis (1st degree)
Germany, Federal Rep.	1975	X-ray fluorescence equipment	Carelessness and technical faults during repair	1	Estimated dose of 30 Gy to the fingers; reddening of two fingers after 10 days
Germany, Federal Rep.	1975	Welding seam test of x-ray equipment	Carelessness and technical defects	1	Estimated dose of 2 Gy to the stomach region
Germany, Federal Rep.	1976	X-ray equipment	Inexpert handling of equipment	1	Estimated whole-body dose of 1 Gy; reddening of skin after 24 hours and radiation after-effects
Germany, Federal Rep.	1980	Radiogram unit	Defective equipment	2	Estimated dose of 23 Gy to the hand and an effective dose of 0.2 Sv
Germany, Federal Rep.	1981	X-ray fluorescence equipment	Carelessness	1	Partial body exposure with 20–30 Gy dose to the right thumb; extensive tissue damage developing over several months
Germany, Federal Rep.	1983	X-ray equipment	Defective equipment	1	Partial body exposure to regions of the body of about 6–12 Gy; localized physical changes
Hungary Györ	1977	Industrial defecto-scope	Failure of equipment to withdraw sources into its container	1	Whole-body dose of 1.2 Gy; slight nausea, changes in blood and increased frequency of chromosomal aberrations; observation and sedative therapy
Hungary Tiszafured	1984	^{192}Ir industrial defectoscope	Failure of equipment and careless handling of source	1	Whole-body dose of 46 mGy; 20–30 Gy estimated for fingers of left hand; radiation burns on fingers of left hand; irreversible necrosis at tip of one finger, surgically removed; slight increase in chromosomal aberrations

Table 40 (continued)

Country / location	*Year of accident*	*Type of installation or operation*	*Main cause of exposure*	*Persons affected*	*Nature of exposure and health consequences*
Italy [a] Brescia	1975	^{60}Co industrial radiography source	Lack of safety systems on conveyor entry point	1	Whole-body dose of 10 Gy; haematopoietic syndrome; death after 13 days
Indonesia Badak, East Borneo	1982	^{192}Ir industrial radiography source	Repair of the source by the operator	1	Estimated doses of 0.77 Gy to the whole body, 0.64 Gy to the gonads and 11.7 Gy to the hands; oedema and suppuration of the hands
Indonesia Cirebon, West Java	1987	Industrial radiography x-ray machine	Repair of shutter while machine was in operation	1	Dose to dorsum of one hand in excess of 10 Gy; oedema and suppuration of the affected hand
India Vikhroli, Bombay	1982	^{192}Ir pencil source	Failure of security during transport of source; source lost and found by a railway worker	1	Dose of 1.5–35 Gy to skin in the region of the groin and whole-body dose of 0.4–0.6 Gy; severe radiation burns in pelvic region with excruciating pain
India Mulund, Bombay	1983	^{192}Ir projector	Operation by untrained personnel	1	Dose to the skin of 20 Gy and to the whole body of 0.6 Gy; severe damage to fingers, four of which were amputated
India Visakhapatnam	1985	^{60}Co radiography projector	Violation of safe working practices and lack of maintenance	2	Skin dose of 10–20 Gy to operator and 0.18 Gy to an assistant; damage to fingers, one finger amputated
India Yamunanager	1985	^{192}Ir radiography projector	Violation of safe working practices associated with power failure in the workplace	2	Doses of 8–20 Gy to hands of both operators; damage to fingers; two fingers amputated from each individual
India Hazira, Gujarat	1989	^{192}Ir radiography projector	Failure of safety management and improper maintenance	1	Dose of 10 Gy to fingers and whole-body dose of 0.65 Gy; radiation burns on fingers of both hands; fingers amputated
Iraq [a]	1975	^{192}Ir radiography source		1	Whole-body dose of 0.3 Gy plus localized exposure of hand
Israel Soreq	1990	^{60}Co irradiation facility	Improper entry procedures and maintenance	1	10–20 Gy whole-body dose; died 36 days later
Norway [c] Kjeller	1982	^{60}Co industrial irradiation facility	Failure of safety device and failure to follow procedures	1	Whole-body dose of 22 Gy; death after 13 days
Peru Zona del Oleoducto	1977	^{192}Ir source	Untrained personnel and lack of supervision; equipment neither registered nor authorized	3	Maximum doses of 164 Gy to hands; 0.9 Gy to lens of the eye; 2 Gy to the whole body; amputation of fingers of two people and effects on left hand of one
South Africa Sasolburg, Tranvaal	1977	^{192}Ir industrial radiography source	Faulty operation of pneumatically operated container and monitor; carelessness of operator	1	Whole-body dose 1.16 Gy; amputation of 2 fingers, rib removal and skin grafts
South Africa Witbank, Transvaal	1989	^{192}Ir industrial radiography source	Detached source; negligence of radiographer (source not properly attached) and failure of portable monitor to register detached source	3	Whole-body doses of three workers; 0.78, 0.09 and 0.1 Gy, computed effective dose to the most exposed was 2.25 Sv; most exposed worker: amputation of right leg at the hip after 6 months and amputation of 3 fingers after one year

Table 40 (continued)

Country / location	*Year of accident*	*Type of installation or operation*	*Main cause of exposure*	*Persons affected*	*Nature of exposure and health consequences*
South Africa Sasolburg, Tranvaal	1990	^{60}Co industrial radiography source	Source left behind after radiography work; loss not detected due to inadequate monitoring, source handled by 6 people	6	Cytogenetic analysis indicated that three people received whole-body doses in excess of 0.1 Gy with a maximum of 0.55 Gy; source handled for periods of 5–20 minutes, but local doses could not be estimated with any accuracy; right hand amputated 10 cm above wrist in one case; patches of sensitive skin on fingers of another; blistering of fingers in two other cases
Switzerland	1992	^{192}Ir radiography source	Jammed 700 GBq source released by hand	1	Erythema of fingers: 3.5 to 10 Gy
USSR [a]	1975	^{192}Ir irradiation facility		2	Whole-body doses of 3 and 5 Gy; dose to hands over 30 Gy
USSR [c]	1976	^{60}Co irradiation facility		1	Whole-body dose of 4 Gy; radiation sickness, haematopoietic syndrome
USSR [a]	1980	^{60}Co irradiation facility		1	Dose of 50 Gy to lens of eye
United Kingdom	1977	Filling gaseous tritium light sources	Broken inlet manifold led to the release of escape of 11–15 TBq of tritium	2	Whole-body doses: 0.62 and 0.64 Sv
United Kingdom [b]	1977	^{192}Ir radiography source	Operator working in a confined area held source for 90 seconds while radiographing a weld	1	Cytogenetic dosimetry estimated an equivalent whole-body dose <0.1 Gy; radiation burns on three fingers
United Kingdom [b]	1978	^{192}Ir radiography source	Radiographer deliberately overexposed himself	1	Cytogenetic dosimetry estimated an equivalent whole-body dose of 1.52 Gy; no localized skin reactions
United Kingdom [b]	1983	Gamma radiography source	Inadvertent exposure of radiographer	1	Whole-body dose of 0.56 Gy
United Kingdom	1991	Industrial radiography	Chronic incidents over 14 years	1	30 Gy to fingers, parts of two fingers amputated. Estimated whole-body dose (chronic) of ≥ 10 Gy. Died of acute myeloid leukaemia
United Kingdom	1993	150 kV radiography unit	Improper procedures	1	Erythema of hands leading to necrotic ulceration; estimated acute dose ≥ 30 Gy
United States [c] Pittsburgh	1976	^{192}Ir radiography source		1	Dose of 10 Gy to hand
United States [c] Rockaway	1977	^{60}Co industrial irradiation source		1	Whole-body dose of 2 Gy
United States [c] Monroe	1978	^{192}Ir radiography source		1	Localized exposure of hand; amputation of finger
United States [c] Los Angeles	1979	^{192}Ir radiography source	Source found by worker and put in his pocket for 45 minutes	5	Whole-body exposure of 1 Gy and localized exposures of hand to one person; localized exposure of hands of four others

Table 40 (continued)

Country / location	*Year of accident*	*Type of installation or operation*	*Main cause of exposure*	*Persons affected*	*Nature of exposure and health consequences*
United States [c] Oklahoma	1981	^{192}Ir radiography source		1	Whole-body and localized exposures
United States	1991	Irradiation facility	Exposure to dark current during maintenance	1	55 Gy to fingers, most of which required amputation
Tertiary education and non industrial accelerators					
German Democratic Rep. Halle	1975	X-ray fluorescence unit	Carelessness	1	Dose of 1.2−2 Gy to middle finger of left hand; acute radiodermatitis (1st degree)
German Democratic Rep. Rossendorf	1980	Radiochemical laboratory	Defect in protective glove led to contamination with ^{32}P	1	Dose of 100 Gy to the skin of the left hand; no clinical symptoms
German Democratic Rep. Berlin	1981	Analytical x-ray unit	Carelessness	1	Dose of 5 Gy to the left hand; acute radiodermatitis (1st degree)
German Democratic Rep. Berlin	1982	Analytical x-ray unit	Carelessness	1	Dose of 6−18 Gy to the right forefinger; acute radiodermatitis (2nd degree)
German Democratic Rep. Leipzig	1983	Radiochemical laboratory	Explosion of vial containing a ^{241}Am solution	1	Committed effective dose of 0.076 Gy
German Democratic Rep. Jena	1988	Analytical x-ray unit	Carelessness	1	Dose of 3 Gy to left hand; acute radiodermatitis (1st degree)
German Democratic Rep. Trustetal	1988	Analytical x-ray unit	Technical defect	2	Maximum dose of 4 Gy to the hand of one person; acute radiodermatitis (1st degree) in one person
Germany, Federal Rep.	1979	X-ray equipment	Defective equipment	1	Estimated dose to part of the hand 20 Gy and effective dose of 0.6 mSv
Peru Lima	1984	X-ray diffraction equipment	Fault of supervision, deliberate exposure from lack of knowledge of risk; equipment not registered with authorities	6	Localized doses of 5−40 Gy to fingers; skin burns and blistering leaving residual scar tissue
USSR [a]	1977	Protein accelerator		1	Localized dose of 10−30 Gy to hands
USSR [a]	1978	Electron accelerator		1	Localized dose of 20 Gy to hands
United States [c]	1978	Accelerator		1	Localized exposure of abdomen, hands and thighs
Viet Nam Hanoi	1992	Research accelerator	Improper entry to adjust sample in beam	1	10−15 Gy to hands, fingers and one hand amputated

Table 40 (continued)

Country / location	*Year of accident*	*Type of installation or operation*	*Main cause of exposure*	*Persons affected*	*Nature of exposure and health consequences*
Medical uses of radiation					
Argentina Tucuman	1975	^{60}Co teletherapy	Failure of source's mechanical mechanisms	2	Technician and physician both received high doses to fingers; radiation burns on fingers
Argentina Parana	1979	Diagnostic radiology	Faulty wiring led to emission of x rays when the top of the fluoroscope was open	1	Auxiliary nurse received whole-body dose of 0.94 Gy; slight depression of bone marrow
Argentina La Plata, B.A.	1982	X-ray therapy facility	Operator looked through window while changing x-ray tubes without recognizing system was energized	1	Whole-body dose of 0.12 Gy and dose of 5.8 Gy to lens of eye; cataracts in both eyes
Argentina Buenos Aires	1983	^{60}Co teletherapy	Source jammed during transfer	2	Doses of 0.66 and 0.67 Gy, respectively, to the thorax; slight bone marrow depression
Germany, Federal Rep.	1975	X-ray equipment	Probably carelessness in maintenance	1	Dose in excess of 1 Gy to head and upper torso
Germany, Federal Rep.	1977	^{192}Ir radiogram unit	Defective equipment	1	Estimated dose to hand of about 5 Gy and effective dose of 0.01 mSv; temporary reddening of fingers
India Ludihana	1980	Radiotherapy (telegamma)	Defective equipment (mercury leaked out through shutter)	3 [d]	Doses of 0.25, 0.4 and 0.5 Gy; no adverse health effects observed
United Kingdom [b]	1975	^{60}Co radiotherapy source	Source jammed in an unshielded position during servicing	2	Personal dosimeters recorded doses of 0.52 and 0.4 Sv
United Kingdom [b]	1977	^{125}I	Accidental contamination of laboratory workers	2	Thyroid dose of 1.7 Gy to one person from an intake of about 1 MBq; a low dose to other person
United Kingdom [b]	1982	X-ray radiography	Inadvertent exposure to x rays	1	Personal dosimeter recorded a dose of 0.32 Sv
United Kingdom [b]	1985	^{125}I	Technician cut his finger while wearing a glove contaminated with iodine-125; sucked cut finger, which resulted in an intake of about 740 MBq	1	Thyroid dose of about 400 Gy
United Kingdom [b]	1986	^{60}Co radiotherapy source	Exposure during source changing	1	Dose of 15 Gy to the hand; erythema and blistering appeared two weeks later

a Data from [I22].
b Data comprise a summary of cases of accidental exposure for which chromosome aberration analysis have been undertaken [L7].
c Data from [R3].
d Unclear whether exposed persons were workers or patients.

Table 41
Other accidents of interest with clinical consequences
Data from UNSCEAR Survey of Occupational Exposures

Country / location	*Year of accident*	*Type of installation or operation*	*Main cause of exposure*	*Persons affected*	*Nature of exposure and health consequences*
Algeria	1978	^{192}Ir radiography source	Lost source	1	1 fatality (member of public)
Brazil Goiania	1986	^{137}Cs radiotherapy source	Abandoned source	~300	21 people in excess of 1.0 Gy (up to 7 Gy): 4 died; many with lesions, 249 with internal contamination
China Xinghou	1992	Former ^{60}Co irradiation facility	Farmer working on the site demolishing facility picked up source: it went with him to hospital	14	14 persons were exposed to >0.25 Gy: 3 received doses >8 Gy and died
Estonia Tammiku	1994	Source from part of an irradiator	Abandoned source and poor source security	6	Whole-body exposure up to 4 Gy, variety of localized exposure up to 1,800 Gy; 1 death
France	1995	Density gauge ^{137}Cs	Handled source (7.4 GBq)	1	Erythema of hands
France	1995	^{192}Ir gamma radiography	Direct handling of 1 TBq source	1	Erythema of hands: estimated local dose >30 Gy
Georgia Lilo	1996/7	^{137}Cs Training sources	Improper management (source security) of sources in a training facility	11	Several lesions of varying seriousness; several suffered vomiting
Iran	1996	^{192}Ir radiography	Poor procedures	1	3 Gy whole-body dose, 50 Gy to chest
Japan Tokai Mura	1999	Reprocessing research	Criticality	3	2 fatalities (17 Gy, 8 Gy) and one other with whole-body dose of 3 Gy
Morroco	1978	^{192}Ir radiography source	Lost source	1	8 fatalities in the public
Turkey Instanbul	1993-1998	Medical therapy sources	Poor source security	18	Five persons with acute radiation (up to 3 Gy) syndrome, one with lesions on one hand
Russian Federation Kremler	1997	Nuclear weapons research facility	Criticality accident	1	5-8 Gy whole-body dose; death after 3 days
Thailand Bangkok	2000	^{60}Co radiotherapy sources	Poor source security leading to three old therapy units ending up in a scrapyard	10	Ten persons were hospitalized of which three died

Table 42
Summary from Radiation Emergency Assistance Centre / Training Site (REAC/TS) radiation accident registries [C7]

Type of use	*Number of accidents*
Criticalities	
Critical assemblies	9
Reactors	7
Chemical operations	6
Total	22
Radiation devices	
Sealed sources	202
X-ray devices	78
Accelerators	23
Radar generators	1
Total	305
Radioisotopes	
Transuranics	26
Tritium	2
Fission products	11
Radium spills	1
Diagnosis and therapy	38
Other	6
Total	84
Total of all	411

Table 43
Worldwide occupational exposures (1990–1994)

Practice	Monitored workers (thousands)	Average annual collective effective dose (man Sv)	Average annual collective effective dose per unit energy generated (man Sv per GW a)	Average annual effective dose (mSv)		Distribution ratio	
				Monitored workers	Measurably exposed workers	NR_{15}	SR_{15}
Nuclear fuel cycle							
Mining	69	310	1.72	4.5	5.0	0.10	0.32
Milling	6	20	0.11	3.3		0.00	0.01
Enrichment	13	1	0.02	0.12		0.00	0.00
Fuel fabrication	21	22	0.1	1.03	2.0	0.01	0.11
Reactor operation	530	900	3.9	1.4	2.7	0.00	0.08
Reprocessing	45	67	3.0	1.5	2.8	0.00	0.13
Research	120	90	1.0	0.78	2.5	0.01	0.22
Total	800	1 400	9.8	1.75	3.1	0.00	0.11
Medical uses of radiation							
Diagnostic radiology	950	470		0.50	1.34	0.00	0.19
Dental practice	265	16		0.06	0.89	0.00	0.24
Nuclear medicine	115	90		0.79	1.41	0.00	0.10
Radiotherapy	120	65		0.55	1.33	0.00	0.15
Total [a]	2 320	760		0.33	1.39	0.00	0.14
Industrial uses of radiation							
Radiography	106	170		1.58	3.17	0.01	0.23
Radioisotope production	24	47		1.93	2.95	0.02	0.25
Other	570	140		0.25			
Total [b]	700	360		0.51	2.24	0.00	0.25
Natural radiation							
Coal mining	3 910	2 600		0.7			
Other mining	760	2 000		2.7			
Mineral processing, etc.	300	300		1.0			
Exposure above ground (radon)	1 250	6 000		4.8			
Aircrew	250	800		3.0			
Total	6 500	11 700		1.8			
Defence activities							
Weapons	380	75		0.19			
Nuclear ships and support	40	25		0.82			
Total	420	100		0.24			
Miscellaneous uses of radiation							
Education	310	33		0.11	1.1	0.00	0.07
Veterinary medicine	45	8		0.18	0.62	0.00	0.02
Total	360	40		0.11	1.0	0.00	0.05
Total of all uses							
Man-made	4 600	2 700		0.6	2.0	0.00	0.13
Natural	6 500	11 700		1.8			
Total	11 100	14 000		0.1			

a These totals includes a component from all other medical uses which is not shown separately.
b These totals includes a component from all other industrial uses which is not shown separately.

Table 44
Trends in worldwide occupational exposures from man-made sources of radiation

Source	*Average annual collective effective dose (man Sv)*				*Average annual effective dose (mSv)*				
					Monitored workers				*Measurably exposed workers*
	1975–1979	*1980–1984*	*1985–1989*	*1990–1994*	*1975–1979*	*1980–1984*	*1985–1989*	*1990–1994*	*1990–1994*
Nuclear fuel cycle	2 300	3 000	2 500	1 400	4.1	3.7	2.9	1.75	3.1
Defence activities	420	250	250	100	1.3	0.71	0.66	0.24	
Industrial uses of radiation [a]	800	900	490	360	2.1	1.8	1.2	0.51	2.2
Medical uses of radiation	1 000	1 140	1 030	760	0.78	0.60	0.47	0.33	1.4
Education/veterinary [a]	70	40	20	40				0.11	1.0
Total	5 490	5 330	4 290	2 700	1.9	1.4	1.1	0.6	2.0
	Average annual number of monitored workers (thousands)				*Normalized collective effective dose [man Sv (GW a)$^{-1}$]*				
	1975–1979	*1980–1984*	*1985–1989*	*1990–1994*	*1975–1979*	*1980–1984*	*1985–1989*	*1990–1994*	
Nuclear fuel cycle	560	800	880	800	18 [a]	17 [a]	12 [a]	9.8	
Defence activities	310	350	380	420					
Industrial uses of radiation [a]	390	510	400	700					
Medical uses of radiation	1 280	1 890	2 220	2 320					
Education/veterinary [a]	140	180	160	360					
Total	2 680	3 730	4 040	4 600					
	NR_{15}				*SR_{15}*				
	1975–1979	*1980–1984*	*1985–1989*	*1990–1994*	*1975–1979*	*1980–1984*	*1985–1989*	*1990–1994*	
Nuclear fuel cycle	0.20	0.16	0.10	0.01	0.63	0.55	0.42	0.11	
Defence activities									
Industrial uses of radiation [a]	0.010	0.007	0.009	0.00	0.35	0.28	0.31	0.25	
Medical uses of radiation	0.003	0.002	0.009	0.00	0.14	0.10	0.24	0.14	
Education/veterinary [a]				0.00				0.07	
Total	0.051	0.040	0.030	<0.01	0.45	0.40	0.36	0.13	

a For 1975-1989 the data previously reported for education was subsumed into industrial uses of radiation. In this report the figures for 1975–1989 have been adjusted to remove this component from industrial uses to permit better comparisons.

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