SOURCES AND EFFECTS OF IONIZING RADIATION

United Nations Scientific Committee on the Effects of Atomic Radiation

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NOTE

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ANNEX D

Occupational radiation exposures

CONTENTS

INTRODUCTION

1. Many individuals are exposed to radioactive materials or radiation sources in the course of their work. The Committee has been interested in evaluating occupational radiation exposures to determine the annual collective dose to workers in various sectors of industry. For purposes of comparison, the doses have often been expressed in terms of some normalized measure of the practice. The total collective dose has been assessed as a measure of the radiation-induced detriment to these individuals.

2. Occupational radiation exposures are monitored in the workplace for the purposes of controlling doses to individuals and demonstrating compliance with occupational exposure limits. Differences exist among countries, however, in the procedures adopted for the monitoring and reporting of occupational exposures; these reflect, inter alia, differences in regulatory systems, in regulatory requirements, in the size of the country, in the uses made of ionizing radiations and in the nature and scale of the radiation protection problems anticipated [D6, G4, G5]. As a result, monitoring data are not always collected and reported in a comparable fashion. This has implications in making valid comparisons between data reported by different countries and, to a lesser extent, between data for different uses of ionizing radiation within a given country. The Committee has adopted a number of assumptions and developed a number methodological approaches for data evaluation to overcome, or at least minimize the impact of, differences in the monitoring and reporting of occupational exposures. This, in turn, has had some effect on data collection and reporting practices.

3. Much progress has been made in the assessment and evaluation of occupational exposures since the Committee's first comprehensive treatment of the topic in the UNSCEAR 1977 Report [U4]. Improvements in the quality of reporting and collation of data have largely been responsible for the progress. There remain, however, areas where adequate data and analyses are lacking and where further investigations are needed to elucidate trends. In the UNSCEAR 1982 Report [U3], occupational exposures were reviewed and a number of recommendations were made for analyses of data that would give much clearer indications of the occupational exposures in all areas of work. Particular attention was drawn to the need for data on the pattern of dose accumulation over a working lifetime, especially for those occupations where higher levels of exposure are encountered, and to the benefits, in terms of facilitating a reliable estimate of collective dose, of reporting monitoring data in narrower bands of individual dose, especially at high doses. A more limited analysis of occupational exposures was undertaken in the UNSCEAR 1988 Report [U1] with updating of the levels of exposure in the nuclear power industry, in the medical uses of radiation and in selected groups exposed to natural radiation.

4. The analysis of occupational exposures in this Annex represents a continuation of the earlier work of the Committee. The main objectives of this continuing analysis are:

(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 risk and distribution of risks in a workforce and for subgroups within it;

(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 (the contributions made by exposures of members of the public are assessed in other Annexes);

(c) to analyse trends with time in occupational exposures in order to evaluate the effects of changes in regulatory standards or requirements (e.g. changes in dose limits, increased attention given to reducing doses to as low as reasonably achievable), new technological developments, modified working practices and radiation protection programmes more generally;

(d) to compare exposures in different countries and to estimate the worldwide levels of exposure for each major use of ionizing radiation;

(e) to evaluate data on accidents involving the exposure of workers to levels of radiation that have caused clinical effects.

Within this context, the purpose of this Annex is to provide a comprehensive and structured analysis of the levels and trends in occupational exposures over the period 1975-1989. Consideration is given to annual and cumulative individual doses, to annual collective doses and their magnitudes per unit practice and to accidents involving high exposures and clinical effects. Particular emphasis is given to those occupations not considered in the UNSCEAR 1988 Report [U1], to those where the need for more information was identified by the Committee in the UNSCEAR 1982 Report [U3] and to those occupational subgroups which, in general, are exposed significantly *in excess* of the average. There is no intention to evaluate the totality of radiation exposures that may be received by

people while at work of any nature. Consideration is limited to those occupations where the nature or circumstances of the work undertaken may lead to significant additional exposure, at least to some members of the workforce.

5. This analysis enables broad comparisons to be made between occupational exposures arising in various industrial and medical activities and between countries. From longer-term monitoring, trends in average individual doses and collective doses from particular practices or entire industries can be assessed and changes in underlying dose distributions can be examined. Trends in doses with time can be assessed in terms of a wide variety of quantities of potential interest (e.g. changes in regulatory standards, technological advances etc.).

6. To obtain the data needed for this review, the Committee has undertaken a survey of occupational radiation exposures worldwide by means of a questionnaire to countries with significant numbers of workers involved in radiation-related activities. This questionnaire specifically requested data on annual individual and collective occupational exposures incurred in operations of the nuclear fuel cycle, in other industrial uses of radiation, in medical uses of radiation and data on accidents with the potential to cause clinical effects. From the extensive and detailed annual data submitted, the Committee computed averages for the five-year periods 1975-1979, 1980-1984 and 1985-1989 to indicate representative average annual values and the basic trends. The assessment has benefited from the substantial database that has been provided, for which the Committee gratefully acknowledges the collaboration of so many countries. Those countries responding to the UNSCEAR Survey of Occupational Exposures are listed in Part A of the References.

I. ANALYSIS OF OCCUPATIONAL DOSE DISTRIBUTIONS

A. DOSE MONITORING DATA

7. The main function of monitoring in the workplace is to provide information for the control and further reduction, where appropriate, of exposures and to ensure satisfactory working conditions. This entails providing the information necessary for estimating the exposure of workers in terms of those quantities in which the basic limits, either primary or secondary, are expressed. However, none of these quantities (e.g. the effective dose, the equivalent dose in a tissue or organ and the intake of a radionuclide) can, in practice, be measured directly, so they must be estimated on the basis of other measured or assessed quantities. Individuals are monitored using equipment carried on their person (e.g. film badge, personal air sampler etc.) or by measuring the quantities of radioactive materials in their bodies or in excreta. Models appropriate for the exposure conditions of interest are used to estimate the relevant dosimetric quantities from these measurements; in general, the modelling approach is chosen cautiously to ensure that the risk of underestimating the exposure of an individual is acceptably small. In some cases exposures are assessed from monitoring of the working environment and knowledge of the habits and location of the workforce.

8. The nature and type of the measurements made and the realism and complexity of the model or models used to interpret them may vary considerably with the exposure conditions and their potential significance. Differences in these inevitably lead to different levels of conservatism in the doses reported or recorded in monitoring programmes. Such differences place limitations on the extent to which direct comparisons can be fairly made between reported data. Where these limitations may be of practical significance for the data included in this Annex, they are identified.

1. Quantities measured

9. *External exposure.* Film, thermoluminescent and other personal dosimeters are used for monitoring individual exposures to external radiation. The choice of dosimeter in any particular circumstances will be influenced by the nature of the radiations likely to be encountered. Dosimeters normally provide a measure of the equivalent dose in the skin in the immediate vicinity of the dosimeter and to immediately underlying tissue in this region. They do not, in general, provide an estimate of the absorbed dose or equivalent dose in other organs or tissues, which in principle need to be assessed to determine the effective dose. The relationship between the dosimeter measurement and the doses in particular organs and tissues of the body is influenced by many factors, such as the type, quality and spatial extent of the radiation, the orientation of the worker relative to the radiation field, the position and composition of the organs in the body etc. Several of these factors will be functions of both time and position in the workplace.

10. Practical guidance on measurement quantities that could be related to the effective dose equivalent and to the dose equivalent in the skin was issued by ICRU in 1985 [I14]. For environmental or area monitoring, the ambient dose equivalent, $H^*(d)$, for strongly penetrating radiation and the directional dose equivalent, H(d), for weakly penetrating radiation were introduced. For individual monitoring, the individual dose, penetrating, $H_p(d)$, and the individual dose, superficial, $H_s(d)$ were introduced. The relationships between these quantities and the effective dose equivalent, H_E, were discussed by ICRP [I3] and ICRU [I14, I15].

11. Some further alterations in radiation quantities have been made. The ICRU recommended in 1992 use of the personal dose equivalent, $H_p(d)$, for individual monitoring, which combines the concepts of the individual dose, penetrating and the individual dose, superficial [I16]. The ICRP introduced in 1991 the effective dose, E, which incorporates tissue weighting factors as in the effective dose equivalent, H_E, albeit for additional tissues specified and with revised numerical values [I7]. The adjustment of the absorbed dose required to reflect radiation quality has been changed by the introduction of radiation weighting factors. An analysis of the relationships between these radiation quantities will be issued by a joint task group of ICRP and ICRU. It can be assumed that the quantities introduced by ICRU provide reasonable approximations of the effective dose and equivalent dose in the skin when these quantities are calculated using the relationships between quality factors and linear energy transfer given in ICRP Publication 60 [I7].

12. In most practical situations, dosimeters provide reasonable approximations to the personal dose equivalent $H_p(d)$ at least at the location of the dosimeter. In situations where the exposure of the body is relatively uniform, it is common practice to enter the dosimeter reading, suitably calibrated, directly into the dose records as a surrogate for the effective dose. However, because the personal dose equivalent generally provides an overestimate of the effective dose, this practice results in an overestimation of 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 could be substantial. For photon energies below ~50 keV it can exceed a factor of 2, depending on the orientation of the body.

13. 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 analyses may be 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) lead, 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 comparisons are made with doses arising elsewhere.

14. 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 further assumed that the dose from natural background radiation has been subtracted from the reported results and that medical radiation exposures have not been included. The Committee also recognized that it is almost always the reading from the dosimeter, suitably modified by calibration factors, that is reported, without consideration of 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 to adopt, in particular as most data are for external exposure of the whole body to relatively uniform photon radiation of moderately high energy. In situations 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 will result in an overestimate of effective doses, which then need 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. Appropriate qualifications of the reported data are made in those cases where the adoption of the above convention may lead to significant misrepresentation of the actual doses.

15. ***Internal exposure.*** The assessment of internal doses from the intake of radioactive material into the body is, in general, more difficult than the measurement of external doses. It is impossible to measure directly the internal dose received by an individual. Instead, it must be calculated based on the quantity and distribution of radioactive material in, or estimated to be taken into, the body, metabolic data, the type and energy of radiation emitted, the fraction

of the emitted energy absorbed by various organs and tissues etc. Various types of monitoring are undertaken to aid the evaluation of internal exposures, depending on the radionuclide concerned and the mode of exposure. These include the use of personal air samplers and/or area monitoring to assess intakes by inhalation, the biological monitoring of excreta and the external counting of the whole or parts of the body.

16. The level of internal contamination, and subsequently dose, is easy to determine by biological monitoring for some radionuclides (e.g. tritium, at least in inorganic form) but very difficult for others (e.g. ^{239}Pu), especially at long times after intake or in cases of multiple intake. In general, the uncertainty associated with the estimation of effective doses from the intake of radionuclides into the body is much larger than that associated with external dosimetry; however, it very much depends on the nuclide in question, the techniques used and the level of contamination.

17. In practice there are few occupations for which exposures from internal contamination are significant. The costs and practical difficulties of providing a personal monitoring service produce strong pressures for designs that reduce internal exposures below levels where continuous personal monitoring is necessary. Historically, in most organizations where internal exposures were potentially significant, estimates were made of the body (or organ) content of a radionuclide, or groups of radionuclides, as a fraction of the Maximum Permissible Body Burden, and the results of the monitoring were usually expressed in these terms. The situation is changing, however, in particular in those countries that have given regulatory effect to the recommendations of the ICRP in its Publication 26 [I1]. In these countries, the results of monitoring internal exposures are now being reported in terms of the committed effective dose from intakes within the year of interest; in general, however, the contribution made by internal exposure is small. These aspects are addressed further in paragraph 27.

18. The few occupations for which internal exposure is potentially significant are uranium mining and milling (inhalation of radon daughters and ore dust); underground work in general, and in particular other forms of mining (inhalation of radon daughters and dust), the luminizing industry (tritium), the operation of heavy water reactors (tritium), fuel fabrication (uranium), fuel reprocessing (actinides), nuclear weapons production (tritium, uranium and plutonium). Quantitative data, albeit limited in some cases, on internal exposures in each of these areas are included in this Annex. Internal exposures could also be significant during the decommissioning of nuclear installations and in nuclear medicine; however, data are unavailable for these activities.

2. Monitoring practice

19. Decisions on who is to be monitored in a workforce, and to what degree, are influenced by the likelihood of exposures at or above different levels. However, as other considerations, (e.g. practicability and industrial relations) are also relevant, the decisions made by operational managements may differ. The outcome is the lack of a consistent approach to monitoring between industries or between countries or even within an industry or within a country. In Publication 26 and in its earlier publications, the ICRP recommended [I1, I2] that in cases where it is very unlikely that annual doses will exceed three tenths of the dose limit, individual monitoring is not necessary, although it may sometimes be carried out to confirm that conditions are satisfactory.

20. The ICRP recommendations have had, and continue to have, a major influence on monitoring practice. However, the relative ease, low cost and sensitivity of monitoring devices for external radiation means that these are much more widely issued than would be expected from the suggested criteria. The devices having been issued, even trivial doses are often reported, despite the ICRP having recommended a recording level of one tenth of the annual limit. The situation for internal exposures is, however, quite different, with monitoring being undertaken only in those few circumstances where there is a clear need.

21. In Publication 60 [I7], the ICRP has recommended that external radiation should be monitored for all those who are occupationally exposed, unless it is clear that their doses will be consistently low or, as in the case of aircrew, that the circumstances prevent the doses from exceeding an identified value.

22. Different approaches are adopted in designating which workers in a workforce are to be monitored. This is to be expected for the reasons previously addressed (e.g. see paragraph 2). However, such differences, if substantial, could limit the extent to which direct and valid comparisons can be made between reported monitoring data for different occupations or industries and/or between data for the same occupation or industry carried out in different locations. This difficulty can, to some extent, be overcome by making comparisons between data for those measurably exposed [i.e. those for which any dosimeter issued during the year in question recorded a dose in excess of the minimum detectable level (MDL) or, alternatively, in excess of some administratively established reporting level] as opposed to those monitored. Even this, however, does not completely circumvent the problem because there are differences in MDLs (or reporting levels) for different sets of

data. The potential magnitude of this problem can be readily appreciated by reference to the variability in the ratio of the number of persons monitored and those measurably exposed in various occupations. This ratio was found to vary from about 1 to 10 for different occupations in the United States [N1] and over an even greater range in Canada [F2]; a value of about 2 was typical of the nuclear industry in the United States.

23. Because of these difficulties, a distinction is made throughout this Annex between average doses estimated for monitored and measurably exposed workers. When appropriate, indications are given of how data expressed in the different ways can be modified to enable direct and more valid comparison. The implications of these difficulties are largely confined to the evaluation and comparison of the size of the exposed workforce and average levels of individual dose. In general, they do not unduly influence the estimation of the collective dose apart from those cases where individual exposures are mostly very low and the ratio of monitored to measurably exposed workers very high.

3. Recording and reporting practice

24. The way in which occupational exposures are recorded and reported differs significantly between occupations and countries. The more important of these include the recording of doses that are less than the MDL, the assignment of notional doses, the protocol for determining who in the workforce is to be monitored (visitors, administrative staff etc.), the inclusion of contract workers in addition to employees, the recording and reporting of internal exposures and the general way in which occupational exposure distributions are reported.

25. MDLs may differ between occupations and certainly differ between countries. When doses are determined to be less than the MDL, the value recorded in the records may be zero, some pre-designated level or the MDL value itself. These differences affect the comparability of results. It is therefore important that reported data on occupational exposures be accompanied by information on the MDL and how doses less than it were recorded.

26. When dosimeters are lost, or the readings are otherwise not available, notional doses are assigned to an individual dose record. A variety of procedures are used in determining the notional dose. These include the assignment of the appropriate proportion of the annual authorized 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; the assignment of the average dose received by co-workers in the same period etc. 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. Such potential difficulties could be overcome if, in these cases, modified data sets were available in which the notional doses were substituted by doses calculated from the average dose over the remainder of the year for each individual or by the average dose received by co-workers during the period in question. This procedure would only be appropriate for dosimeters lost in routine situations; when high exposures are suspected, such as in accidents, individual dose reconstruction would be a more appropriate basis for determining the dose to be recorded.

27. In the past, internal and external exposures were generally recorded separately and often in different ways, with little or no attempt made to present distributions of the summed exposures. Significant variations also occurred in the reporting levels for internal contamination, and this further enhanced the difficulties of compilation and comparison of statistics on internal exposure. This situation is changing, however, and internal exposures are increasingly being recorded in terms of committed doses from intakes within the year of interest and, moreover, added to any dose received from external sources. The generation of these more complete dose records will enable more valid and reliable comparisons to be made of doses in various occupations and industries. These changes in recording procedures have two implications, however. First, in the transitional period not all dose distributions are likely to be based on the sum of internal and external doses, and due provision will need to be made for this in any comparisons. Secondly, previous estimates of occupational exposures will need to be updated, in particular for those occupations and industries (e.g. fuel fabrication and fuel reprocessing) where internal exposures may have been significant but were not included in the reported data.

28. Two particular features of the way in which occupational dose distributions are reported influence the ease and effectiveness with which the relevant data can be extracted and compared. The first is the categories or types of occupation for which data are commonly reported. Significant differences are apparent in the occupational categories used in different countries. The advantages of reporting data according to a broadly agreed categorization scheme are self-evident, but the difficulties of achieving consensus in this area are not to be underestimated, especially in the light of long-established national

practices, which often will have evolved to accommodate particular national interests and/or concerns. Nevertheless, efforts to achieve greater uniformity in the collection and reporting of data would be of general benefit. The categories used by the Committee for evaluating occupational exposures are given in Table 1. Although the categories are broad, their wider use would simplify and unify the data collection and reporting.

29. The second feature influencing data extraction and comparison is the level of detail or resolution adopted when reporting the distribution of occupational exposures, in particular, at the higher levels of individual dose. Analytical procedures have been developed by the Committee [U3, U4] to enable quantities of interest to be extracted almost irrespective of how the data were reported, but if the data were all reported in a sufficiently detailed and consistent manner, these procedures would be largely unnecessary. Analytical techniques may, however, play a continuing important role in the estimation of future annual and cumulative doses, subject to various assumptions on dose limits or dose constraints in particular occupations. This topic is discussed further in the next Section, where procedures for data reporting are given with a view to achieving greater consistency between the data and facilitating their evaluation and comparison.

30. Finally, two additional points could affect the validity of comparisons between occupational exposures in different groups or within the same group over time: first, whether any administrative changes have occurred in dose recording that may affect the reported doses from one year to another and, secondly, whether the reported doses are complete, in particular whether contract workers as well as employees are included in the statistics. The reported data are not always explicit with regard to these points.

B. CHARACTERISTICS OF DOSE DISTRIBUTIONS

31. Dose distributions are the result of many constraints imposed by the nature of the work itself, 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.

32. The Committee is principally interested in making comparisons of 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), E, which is related to the average level of individual risk;
(b) the annual collective effective dose, S (referred to as M in earlier UNSCEAR Reports), which is related to the impact of the practice;
(c) the ratio, SR, of the annual collective effective dose delivered at annual individual doses exceeding 15 mSv to the total collective dose. SR (referred to as MR in earlier UNSCEAR Reports) provides an indication of the fraction of the collective dose received by workers exposed to higher levels of individual risk. This ratio is termed the collective dose distribution ratio.

33. Another ratio, NR, of the number of workers receiving annual individual doses exceeding 15 mSv to the total monitored or exposed workforce, is reported in many occupational exposure statistics, often when the ratio SR is not provided. The more frequent reporting of the ratio NR is probably due to the ease with which it can be estimated. In the past, this ratio was not used or reported by the Committee because of its potential sensitivity to how the size of the workforce is defined (those monitored, those measurably exposed etc.); consequently, comparisons of values of this ratio reported for different occupations and in different countries would, in general, require some qualification. The ratio SR 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, it is now included in the characteristics reported by the Committee. This change is largely a reflection of the more frequent reporting of the ratio NR in occupational exposure statistics, but it also 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, however, remains the most appropriate basis for comparing data generally.

34. The annual collective effective dose, S, is given by

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

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

$$S = \sum_{j=1}^{r} N_j E_j \qquad (2)$$

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

$$NR_{15} = \frac{N(>15)}{N} \qquad (3)$$

where N(>15) is the number of workers receiving annual doses exceeding 15 mSv. The annual collective dose distribution ratio, SR, is given by

$$SR_{15} = \frac{S(>15)}{S} \qquad (4)$$

where S(>15) is the annual collective effective dose delivered at annual individual doses exceeding 15 mSv.

35. 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 of this. 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.A, 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.

36. The three quantities used in the past by the Committee have provided a useful basis for summarizing and comparing occupational exposures. One of the quantities, the collective dose distribution ratio SR, may, however, become increasingly less useful or informative. In the event that regulatory dose limits are reduced by a significant amount, the fraction of the collective dose arising from annual individual doses in excess of 15 mSv is likely to decrease. The quantity may then cease to serve the purpose intended for it. The Committee believes, therefore, that it would be useful to estimate and report additional values of the collective dose distribution ratio, but for the fraction of the collective dose arising from levels of annual individual dose lower than the previously adopted value of 15 mSv. These collective dose distribution ratios are designated, SR_E, where the subscript E signifies the level of annual individual dose to which the ratio refers. These comments apply equally to the ratio NR.

37. In summary, the following characteristics of dose distributions will be considered by the Committee in its reviews of occupational exposure:

(a) the average annual effective dose (i.e. the sum of the annual dose from external irradiation 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 a value of E of 15 mSv in this Annex and additionally for lower values in the future;
(d) the number distribution ratio, NR_E (the fraction of the workforce exposed to annual doses in excess of E) for a value of E of 15 mSv in this Annex and additionally for lower values in the future;

To facilitate the task of extracting data from dose distributions, persons reporting data are encouraged to include these characteristics explicitly in their dose distributions. In addition to the annual collective dose, it would also be very useful to have information provided so that normalized forms of this quantity can be derived, i.e. expressed in terms of unit practice, for example per reactor or per unit energy generated. This facilitates comparison between practices.

38. Ideally, these characteristics of dose distributions would be evaluated by those reporting the data from the complete, detailed recording of doses to workers within a particular workforce, and they would be presented in the requisite form. In practice, however, this does not always occur. Data on occupational exposures are completed in a variety of forms, some of which do not lead to the explicit presentation of all those quantities of interest to the Committee. In these cases the quantities must be calculated from the data presented, and the Committee has developed analytical

procedures for this purpose. These are summarized below. Further details of the procedures are presented in the UNSCEAR 1982 Report [U3]. The need for the Committee to use such procedures has, however, diminished with time, owing to improvements in and more comprehensive reporting of occupational exposures.

39. In the UNSCEAR 1977 Report [U4] (Annex E), it was noted that many dose distributions exhibit a log-normal character, especially at doses well below the annual dose limit. This property can be readily identified by plotting the cumulative frequency of the number of individuals with doses less than a given level on a probability axis against the logarithm of dose. Where the required information cannot be extracted directly from the reported results, a log-normal fit to the appropriate part of the distribution can be used to extract the collective dose and the fraction of the collective dose delivered in different individual dose ranges. This procedure can also be used, where necessary, to assess collective doses to the large numbers of workers in the lowest dose band, who may receive very low or zero doses but nonetheless are given dosimeters.

40. A variable x is said to be distributed log-normally if the values of $y = \ln x$ are distributed normally. The mean, median and mode of the distribution of y is μ; the variance of the distribution of y is σ^2. The probability that a value of x will lie between x and x + dx is

$$P(x)\,dx = \frac{1}{\sigma\sqrt{2\pi}}\,\frac{1}{x}\,e^{-\frac{(\ln x-\mu)^2}{2\sigma^2}}\,dx \qquad (5)$$

Since the data rarely fit a log-normal distribution over the whole range, the quantity of use is the collective dose S_E, up to a certain annual effective dose E. This is given by

$$S_E = N\int_0^E x\,P(x)\,dx \qquad (6)$$

This can be expressed as

$$S_E = \frac{N}{\sqrt{2\pi}}\,e^{\mu+\frac{\sigma^2}{2}}\int_{-\infty}^{T} e^{-\frac{t^2}{2}}\,dt \qquad (7)$$

where the substitution variable $t = (\ln x - \mu - \sigma^2)/\sigma$. The substitution using t is made to render S_E in the form shown, since tabulations of the cumulative *normal distribution* function are readily available. The choice of the appropriate value of E for each distribution is made by inspecting the data plotted on log probability graph paper; very often 10 or 15 mSv is a convenient value.

41. Graphical techniques are often of sufficient accuracy for analyses of dose distributions and are described both in standard texts [F1] and in the context of occupational dose distribution analysis [B1]. If a straight line is fitted to the plot of the cumulative frequency versus ln E, then the value of E is $(\mu - \sigma)$ at a cumulative frequency of 15.87% and $(\mu + \sigma)$ at a cumulative frequency of 84.13%. S_E can then be obtained from standard tabulations.

42. Alternatively, a wide variety of numerical and/or analytical techniques can be used to evaluate the quantities of interest from the dose distributions. For example, when sufficient data are available, the methods of maximum likelihood or of least squares can be used to obtain the equation for the best-fit line up to an annual dose E, chosen from inspection of the plot; the collective dose up to that value of dose can then be obtained by numerical integration. To estimate the collective dose in the ranges above E, where the dose distribution deviates from log-normal, it may be sufficient to multiply the number of individuals in each dose range by the mid-point dose of the range, if this information is available with adequate resolution. Equally, graphical or various curve-fitting techniques can be employed to evaluate the integral and other quantities of the dose distribution.

43. Investigations by Kumazawa et al. [K1] have shown that the control exercised over doses approaching the dose limit results in a normal distribution of doses in the higher dose ranges, and that a combination of a log-normal and a normal distribution (but not a mixed distribution of them) may provide a more generally applicable means of representing occupational dose distributions. Such hybrid log-normal distributions have been shown to provide a good representation of observed data in many circumstances [E1].

44. The distribution function of a variable x is hybrid log-normal if the values of $y = \ln(\rho x) + \rho x$ $(\rho > 0)$ are distributed normally. The mean, median and mode of the distribution of y is μ and the variance of the distribution of y is σ^2. The probability that a value of x will lie between x and x + dx is given by

$$P(x)\,dx = \frac{1}{\sigma\sqrt{2\pi}}\left(\rho + \frac{1}{x}\right) e^{-\frac{[\ln(\rho x)+\rho x-\mu]^2}{2\sigma^2}}\,dx \qquad (8)$$

where ρ, μ and σ are parameters of the hybrid log-normal distribution. It should be noted that μ and σ^2 do not have the usual meanings of mean and variance for variate x that they have for the normal distribution. The parameter ρ is a measure of the degree of control exercised to avoid approaching or exceeding some level of exposure. As $\rho \to 0$, the distribution tends to

the log-normal distribution; as $\rho \rightarrow \infty$, it tends to the normal distribution (defined only above zero).

45. For a hybrid log-normal distribution, the ratios NR_E and SR_E, are given by

$$NR_E = \frac{\int_E^\infty P(x)\,dx}{\int_0^\infty P(x)\,dx} \text{ and } SR_E = \frac{\int_E^\infty x\,P(x)\,dx}{\int_0^\infty x\,P(x)\,dx} \quad (9)$$

All of these integrals have to be evaluated numerically. Graphical and computational methods for deriving the parameters ρ, μ and σ of the hybrid log-normal distribution that provides the best fit to a given set of data are described in the literature [K1, S1]. Computational techniques for evaluating the above integrals are also available [K2].

46. The hybrid log-normal distribution is finding increasing use in the analysis and reporting of occupational exposures, particularly in the United States, where it has been used by several agencies in their most recent compilations of annual statistics [E3, R2, M3]. One of its uses has been to re-evaluate statistics compiled previously on a simpler basis; its use in this context led the United States Department of Energy [M3] to conclude that collective doses reported in previous years were probably overestimates by, on average, 15%-20%. More importantly, it provides a means to assess the degree of active control used in different occupations to reduce the frequency of annual doses approaching dose limits or other constraints. Similarly, it can be used to predict future trends in dose subject to assumptions on the degree of control exercised over the occurrence of higher individual doses.

47. The hybrid log-normal distribution may also provide a useful means of reporting dose distribution data succinctly. If dose distributions are generally well fitted by the hybrid log-normal form, it would be possible to describe a complete distribution of exposures by specifying the three parameters of the hybrid log-normal distribution function. It would then be possible to generate from these three parameters any characteristic of the dose distribution that may be considered useful now or in the future. Given the flexibility offered by this approach, the merits of reporting occupational exposures in terms of the three parameters of the hybrid log-normal distribution warrants further consideration. The additional computational effort involved in deriving these parameters may impede the wide-scale adoption of this approach.

48. The need for succinct reporting of dose distributions has, however, diminished with the growth and ease of use of computer databases. Vast amounts of data can now be readily stored in an accessible form. Provided occupational exposure databases are created with sufficient resolution, it will be possible, using simple arithmetic techniques, to estimate with adequate precision all of the characteristics presently of interest to the Committee; any other characteristics that might eventually be of interest could likewise be readily evaluated. Access to such databases in the future is likely to reduce the use made by the Committee of empirical fits to dose distributions to extract required quantities. In these circumstances, the future use of empirical fitting by the Committee is likely to be limited to the extraction of quantities of interest from data compiled with inadequate resolution in the past; additionally, the techniques will continue to be used to provide insights into matters such as the influence of dose limits or constraints on the characteristics of dose distributions and for purposes of estimating the magnitude of, and trends in, future annual and cumulative doses.

C. ESTIMATION OF WORLDWIDE EXPOSURES

49. Inevitably, the data provided in response to the UNSCEAR Survey of Occupational Exposures will remain incomplete in terms of estimating worldwide levels of dose. Procedures have therefore been developed by the Committee to derive worldwide doses from the data available for particular occupational categories. Two procedures have been 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.

50. 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 can be achieved 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 part 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,

$$S_w = \frac{1}{f}\sum_{c=1}^{n} S_c \qquad (10)$$

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

$$f = \sum_{c=1}^{n} P_c / P_w \qquad (11)$$

with P_c and P_w the productions in country c and in the world, w, respectively.

51. The annual number of monitored workers worldwide, N_w, is estimated by a similar extrapolation. Because of more limited data, 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 on an annual basis. Values of these quantities have been averaged over five-year periods, and the average annual values are reported in this Annex.

52. For exposures to radiation other than in 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 has seemed to be most practical and reasonable to extrapolate on the basis of gross national product (GNP) of countries. Several considerations influence the choice of this quantity in preference to others, notably the availability of reliable worldwide statistics on gross national products and their potential for general application; the latter is a consequence of the expectation that the gross national product is reasonably correlated with both the level of industrial activity and medical care in a country, characteristics unlikely to be found 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.

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

$$S_w = \sum_{r=1}^{m} S_r \qquad (12)$$

where

$$S_r = \frac{1}{g_r}\sum_{c=1}^{n_r} S_c \qquad (13)$$

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 the GNP of region r, represented by those countries for which occupational exposure data are available and is given by

$$g_r = \sum_{c=1}^{n_r} G_c / G_r \qquad (14)$$

where G_c and G_r are the GNPs of country c and region r, respectively, and are expressed in United States dollars.

54. 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 is adopted. In these cases the regional collective dose is estimated as

$$S_r = G_r \sum_{c=1}^{n} S_c / \sum_{c=1}^{n} G_c \qquad (15)$$

For the purposes of this analysis the world was divided into nine geographic or economic regions comprising: countries of the Organization for Economic Cooperation and Development (OECD), comprising 24 countries; Eastern Europe, including the former USSR; Latin America; Africa, excluding South Africa; the Indian subcontinent; south and south-west Asia; centrally planned economies in east and south-east Asia; non-centrally planned economies in east and south-east Asia and Oceania.

55. 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 where the averaging was performed first on a regional basis prior to summing over all regions. For selected occupational categories, estimates are also made of the number of measurably exposed workers worldwide, M_w. These are estimated on a regional basis from the quotient of annual collective effective dose and the average annual dose to measurably exposed workers.

56. Given the approximate nature of this form of extrapolation, it has been applied not to annual data but to data averaged over five-year periods. Representative data on the gross national product were used for each of the three periods (specifically, 1977, 1983 and 1989) [I17, U11]. The particular years used are of no absolute importance, as it is only the relative values of gross national products within a given period that are relevant to the extrapolation.

D. CUMULATIVE DOSE DISTRIBUTIONS

57. The subject of cumulative and lifetime occupational doses to workers and their distribution for particular workforces is an important one that needs to be addressed. There are, however, few data available in the open literature that either report values directly or allow estimates to be made. Of particular interest are the cumulative or lifetime doses among those groups of workers who regularly experience high average annual effective doses.

58. The Committee has made no assessment of cumulative lifetime doses since the UNSCEAR 1977 Report [U4], when simple linear extrapolation was used to estimate doses for a few categories of workers for whom data on average doses and years of employment were available. The deficiencies in such a simple extrapolation were well recognized, but there was hope that this simple treatment would stimulate more rigorous investigations of the relationship between the rate of accumulation over the years of employment and the total dose received. This hope has not been realized to any great extent, and there still remain few published analyses of cumulative or lifetime doses that the Committee can use as a basis for a thorough assessment.

59. The progress the Committee can make in this area will inevitably be constrained by published data or data made available by national authorities. The published data are reviewed in this Annex, and the distributions of cumulative and lifetime doses in particular occupations are assessed. Given the importance of the topic, it would be useful if national authorities and some large employers would make available other relevant, but so far unpublished, data and could undertake further analyses in this area. It is evident that much progress will be made in this regard in support of epidemiological studies that have been, or are in the process of being, carried out for particular occupational groups. The temporal patterns of individual exposures are essential components of such studies, and it should be possible to extract the required data and report them in a suitably anonymous fashion so that the privacy of the records of individual workers is safeguarded. The protocols under which data were collected for epidemiological studies may, however, in some cases inhibit the use of the data for the purposes of interest to the Committee.

II. THE NUCLEAR FUEL CYCLE

60. The fuel cycle that serves nuclear power reactors used for the generation of electrical energy is a major identified practice giving rise to occupational exposures. Exposures arising from this practice were discussed and quantified in the UNSCEAR 1972 [U5], 1977 [U4], 1982 [U3] and 1988 [U1] Reports, with comprehensive treatment in the 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 more recent years. Consideration is given in this Annex to occupational exposures arising at each major stage of the fuel cycle. As the final stage of 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, 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 source.

61. For each stage of the fuel cycle estimates are made of the magnitude and temporal trends in the annual collective and average individual 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; these quantities can be re-normalized 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, 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 B, "Exposures from man-made sources of radiation". For reactors, several ways of normalizing the data may be appropriate, depending on how the data are used. In this Annex, normalized collective doses are given per reactor and per unit electrical energy generated.

62. 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 from 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 period. 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.

63. In addition to the annual dose, the rate at which dose is accumulated during the career of an individual (cumulative or lifetime dose) is an important statistic in judging the significance of occupational exposures. As mentioned above, however, there are as yet few data available on cumulative or lifetime doses. Accordingly, the subject is not treated separately for each stage of the fuel cycle, but it is addressed in Section II.G for the nuclear fuel cycle as a whole.

64. 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 procedures used by each country that responded to the UNSCEAR Survey of Occupational 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 that have been identified in Table 2, and the 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 Exposures nor, consequently, can they 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

65. Uranium is obtained from ore mined in several countries, with the largest producers within WOCA (World Outside Centrally planned economies Area) being Australia, Canada, France, Namibia, Niger, South Africa and the United States; in addition, uranium exploration and/or production is being undertaken on a smaller scale in several other countries. Data on the annual production of uranium are given in Annex B, "Exposures from man-made sources of radiation". Uranium mining operations involve the removal from the ground of large quantities of ore containing uranium and its decay products at concentrations up to several thousand times the concentrations of these nuclides in the natural terrestrial environment. The concentration of uranium in mined ores is typically between 0.1%-3% U_3O_8 but in exceptional cases may be as high as a few tens of per cent. Mining is carried out by either underground or open-pit methods, which account for most of the uranium produced; in recent years *in situ* solution mining has also been carried out, although this makes only a small contribution to overall uranium production. In some cases uranium is obtained as a by-product of the mining of gold or other metals.

66. Uranium milling operations involve the processing of large quantities of ore to extract partially refined uranium. The process of extraction involves the following steps: crushing, grinding, chemical leaching, separation of the uranium from the leach solution, precipitation, drying and packing of the extracted material. Most mills use an acid leach extraction process, although other processes are in use. The uranium concentrate, often referred to as yellowcake, is used as feed for fuel fabrication plants, where it is further refined, converted and, if necessary, enriched.

67. Both internal exposure and external irradiation may be significant contributors to occupational exposure during uranium mining. Internal exposure

may arise from the inhalation of radon and its decay products and the inhalation of ore dust containing long-lived alpha emitters of the uranium chain. A number of factors will influence the relative contribution of each source, including, among others, the type of mining undertaken (i.e. deep mining or open-pit) and the efficacy of ventilation underground. The main source of internal exposure in underground mines is, in general, the inhalation of radon and its decay products; where these have been reduced to a low level, the inhalation of ore dust may be a significant contributor. In open-pit mines, particularly in dry climates, inhalation of ore dust is likely to be the main source of internal exposure. Because of the confined space underground and practical limitations to the degree of ventilation that can be achieved, internal exposure is of greater significance in underground mines than in open pit mines. Occupational exposure from the inhalation of radon decay products in underground mines was recognized as a major radiological protection problem in the 1960s and early 1970s. In the intervening period much has been done to reduce airborne concentrations of radon and its decay products in mines and, consequently, exposures from this source. Improvements continue but with increasing cost and difficulty as the concentrations are reduced.

68. Occupational exposures from uranium mining in 14 countries, averaged over 1975-1979, 1980-1984 and 1985-1989, are summarized in Table 3; data are reported separately for underground and open-pit mining. The contributions to the totals, where available, of external exposure and internal exposure from inhalation of radon progeny and ore dust are indicated. Some comments on the tabulated doses are necessary however, in particular on the doses from inhalation of radon progeny. In general, in the data reported to the Committee (or published elsewhere), doses from inhalation of radon progeny were estimated on the basis of a conversion factor of 10 mSv WLM^{-1}. In Annex A the annual effective dose from radon progeny for members of the public has been taken to be 1 mSv from indoor exposure (7,000 hours per year) to a radon concentration of 40 Bq m^{-3} or an equilibrium equivalent concentration (EEC) of 16 Bq m^{-3}. Assuming the same numerical relationship between dose and concentration applies to occupational exposures, the value of the conversion factor expressed in units of dose per working level month (WLM) is: 1 mSv ÷ 7,000 hours ÷ 16 Bq m^{-3} x 6.3 10^5 Bq h m^{-3} WLM^{-1} = 5.6 mSv WLM^{-1}. This is consistent with the value of 5 mSv WLM^{-1} suggested in a consultative document issued by ICRP [I13]. While it has been possible to modify reported doses for this change in conversion factor, insufficient data were available to enable the reported data on distribution ratios to be modified. The tabulated values of NR_{15} and SR_{15}, while valid within the context within which they were reported, are strictly applicable to a value of E somewhat less than 15 mSv; the exact value to which they refer will depend on the particular data set, in particular on the relative contribution of radon progeny to the total dose.

69. Estimates of worldwide levels of exposure from uranium mining, also given in Table 3, have been derived by extrapolating the reported production to total world uranium production. The numbers of monitored workers and the annual collective and individual doses, averaged over the same five-year periods, are illustrated in Figure I. The normalized collective dose and the dose distribution ratios are presented in Figure II.

70. Data on national uranium production have been obtained from responses to the UNSCEAR Survey on Occupational Exposures or, in their absence, from OECD [O2]. Worldwide levels of production were obtained as the sum of data reported by OECD [O2], which was limited to WOCA (World Outside Centrally planned economies Area) countries; data reported to UNSCEAR for Czechoslovakia and the German Democratic Republic; and estimates for China and the former USSR. Production in China was estimated from reported collective doses [I10], assuming that the collective dose per unit mass of uranium mined was equal to the average in those countries for which data were available for underground mines in 1985-1989. This rough estimate of annual production in China was assumed, in the absence of better data, to apply throughout the period 1975-1989. The mining of uranium in the former USSR was nominally assumed equal to that estimated for China.

71. The annual amount of uranium mined worldwide, averaged over five-year periods, was 50-60 kt. The production was highest in 1980-1984 and 10%-15% lower in 1975-1979 and 1985-1989. By far the majority of uranium (about 80%) was mined underground in this period, although the contribution from open-pit mining increased with time. About a quarter of a million workers were involved in uranium mining worldwide; 99% of them, on average, were employed in underground mines, with about one third of these in gold mines in South Africa in which uranium is also extracted. The worldwide annual collective effective dose, averaged over 1975-1989, is estimated to have been about 1,300 man Sv, although there is evidence that levels were about 20% lower than this average in the most recent five-year period; open-pit mining made only a minimal contribution to the total (about 1% on average). The average annual effective dose to monitored workers (or more strictly to those workers whose doses were assessed, either from personal or environmental monitoring) in underground mines has declined from about 5.5 to about

4.5 mSv between the first and third five-year periods. In open-pit mining the corresponding doses were lower, declining from about 2.0 mSv to about 1.6 mSv over the same period (Figure I). The normalized collective effective dose from underground mining decreased from about 30 to about 26 man Sv kt^{-1} uranium [6.6 to 5.7 man Sv $(GW\ a)^{-1}$] between the first and third five-year periods; in open-pit mining, the normalized doses were much lower, having decreased from about 1.1 to about 0.3 man Sv kt^{-1} uranium [0.24 to 0.06 man Sv $(GW\ a)^{-1}$] over the same period (Figure II). For uranium mining as a whole, the normalized collective dose decreased from 26 to 20 man Sv kt^{-1} uranium [5.7 to 4.3 man Sv $(GW\ a)^{-1}$].

72. The reporting of data on distribution ratios is less comprehensive than that on other quantities of interest. Moreover, the situation is further complicated by the modification of reported data to take account of the adoption here of a conversion factor of 5.6 mSv WLM^{-1} for exposure to radon progeny compared with a value of 10 mSv WLM^{-1} generally used in the reported data. While reported doses can be readily modified to account for this change, this cannot be done for the reported distribution ratios. In these circumstances consideration is limited here to an analysis of trends in the reported distribution ratios, while recognizing that the ratios strictly are applicable to values of E somewhat less than 15 mSv (moreover, with the value of E differing between countries depending on the relative contribution of inhalation of radon progeny with total dose). For those countries reporting data on distribution ratios, the fraction of the monitored workforce in underground mines in these countries receiving reported annual effective doses greater than 15 mSv declined from 0.39 in 1975-1979 to 0.26 in 1985-1989; the fraction of the reported collective effective dose arising from reported individual doses above the same level also declined, from 0.69 to 0.53 over the same period. It is not possible to be precise with regard to the level of dose to which these ratios apply when using a dose conversion factor of 5.6 mSv WLM^{-1}, but it is of the order of 10 mSv. The distribution ratios in open-pit mining were much smaller; over the same period the reported number distribution ratio, averaged over those countries providing data on this quantity, declined from about 0.005 to 0.0004 and the reported collective dose distribution ratio from 0.026 to 0.006 (Figure II); for the dose conversion factor adopted in this Annex the value of dose to which these ratios apply is within a range of about 10 to 12 mSv. These values for the reported distribution ratios, averaged over the countries which provided such data, can be considered indicative of worldwide levels.

73. The data for individual countries and their trends with time vary considerably about the average worldwide values (see Table 3). For underground mining the average annual effective dose, averaged over the five-year periods, typically varied within a range of 3-20 mSv; Bulgaria was a notable exception. For open-pit mining the corresponding range of variation was typically about 1-5 mSv. The variation in normalized collective effective doses was even greater, between about 1 and 110 man Sv kt^{-1} uranium [0.25 to 25 man Sv $(GW\ a)^{-1}$] for underground mines; doses in Canada, France and the United States were at the lower end of this range and those in Argentina, India and South Africa at the upper end. For open-pit mines the range of variation was about 0.04-16 man Sv kt^{-1} uranium [0.01-4 man Sv $(GW\ a)^{-1}$]. The range of variation between countries for the reported distribution ratios was somewhat smaller than the range for other quantities.

74. Internal exposure makes by far the greatest contribution to the total exposures in underground mining. Averaging over those countries (Australia, Canada, China, Czechoslovakia, France, the German Democratic Republic, India and South Africa) reporting data on at least two of the three main contributors to exposure (in those cases where only two pathways were quantified the contribution of the third was assumed to be zero), about 70% of exposures arose on average from the inhalation of radon daughters, about 3% from the inhalation of ore dust and about 27% from external irradiation. For open-pit mining there was much greater variation reported in the contribution of the respective exposure pathways. In Argentina, external irradiation contributed about 80% and inhalation of radon daughters about 20% to total exposures; the contribution of ore dust was small by comparison. In Canada in 1985-1989 (doses from milling were included in the data for earlier periods), external irradiation and the inhalation of radon daughters were also the main contributors to total exposure (about 50% and 43%, respectively), with a contribution of about 6% from the inhalation of ore dust. The Australian data showed a somewhat different distribution, with the largest contribution from ore dust (about 75%) and external irradiation and radon daughters contributing about 22% and 2%, respectively. Averaging over these three countries during the 1980s, external exposure has contributed about 70% of the total dose and inhalation of radon progeny about 30%; about 4% of the total has arisen from inhalation of dust.

75. Occupational exposures from uranium milling in nine countries, averaged over 1975-1979, 1980-1984 and 1985-1989, are summarized in Table 4. The reported data for milling were modified in the same way as those for mining (see paragraph 68) in respect of exposure from inhalation of radon progeny (i.e.

conversion factor of 5.6 mSv WLM^{-1} adopted, compared with 10 mSv WLM^{-1} used in reported data. The qualifications made in paragraph 68 with respect to the tabulated distribution ratios apply equally here. Estimates of worldwide levels of exposure are also given in Table 4; they were derived by extrapolating to the total world production of milled uranium. Data on the amounts of uranium milled in individual countries were obtained from responses to the UNSCEAR questionnaire or, in their absence, from OECD [O2], subject to the simplifying assumption that the amount of uranium milled in any year was equal to that mined. This same assumption was used in estimating the amount of uranium milled worldwide. The numbers of monitored workers, the annual collective and individual doses, averaged over the five-year periods, the normalized collective dose and the dose distribution ratios are illustrated in Figures I and II.

76. The average number of workers in uranium milling worldwide is much smaller than the number in mining. It increased from about 12,000 in 1975-1979 to about 20,000 since then. The worldwide annual collective effective dose, averaged over the whole period, 1975-1989, is estimated to have been about 120 man Sv. A small downward trend with time is evident, with a decrease of about 10 man Sv between the first five-year period and the subsequent periods. The worldwide average annual effective dose to monitored (or more strictly, assessed) workers in milling decreased from about 10 mSv in 1975-1979 to about 6 mSv subsequently and is somewhat greater than that experienced in underground mining. The normalized collective effective dose from milling has decreased from about 2.4 in 1975-1979 to about 2.0 man Sv kt^{-1} uranium [about 0.5-0.4 man Sv $(GW\ a)^{-1}$] after that time. In comparison, the normalized collective dose from open-pit mining was smaller on average by a factor of about 2 and that for underground mining was more than an order of magnitude greater.

77. Relatively few data have been reported on distribution ratios for milling and, as for mining, interpretation of the data that do exist is complicated by the revision of reported doses to conform with the dose convention used in this Annex for exposure from inhalation of radon progeny. For the reasons set out above (see paragraph 72) consideration is limited to an analysis of the trends in the reported distribution ratios. Averaging over the available data, the fraction of the monitored workforce receiving reported annual effective doses greater than 15 mSv declined, from about 0.4 in 1975-1979 to about 0.2 in 1985-1989; the fraction of the collective effective dose arising from individual doses above that level declined, from about 0.8 to about 0.4 over the same period. It is impossible to be precise with regard to the level of dose to which these ratios refer when using a dose conversion factor of 5.6 mSv WLM^{-1} for inhalation of radon progeny, but it is of the order of 12 mSv. In the absence of more comprehensive data, these values of the distribution ratios can be considered indicative of worldwide levels.

78. The data for individual countries and their trends with time vary considerably about the average worldwide values (see Table 4). The average annual effective dose to monitored (or more strictly, assessed) workers, averaged over the five-year periods, varied within the range of about 0.1-13 mSv. The variation in the normalized collective effective doses was even greater, from less than 0.1 to about 30 man Sv kt^{-1} uranium [less than 0.02 to about 6 man Sv $(GW\ a)^{-1}$]; doses in Canada, South Africa and the United States were towards the lower end of this range and those in Czechoslovakia, the German Democratic Republic and India towards the upper end.

79. Internal exposure makes by far the greatest contribution to total exposures in milling. Averaging over those countries (Australia, Canada, Czechoslovakia, German Democratic Republic and India) reporting data on each of the three main contributors to exposure in the 1980s, about 38% of exposures arose from the inhalation of radon daughters, about 47% from inhalation of ore dust and about 15% from external irradiation. Considerable variation is, however, evident between countries in the contributions of the respective exposure pathways. The data for the German Democratic Republic are comparable with the average values; those for Australia and Czechoslovakia indicate much greater contributions from the inhalation of ore dust, while for India, the contribution of ore dust was reported as negligible in comparison with the other exposure pathways.

B. URANIUM ENRICHMENT AND CONVERSION

80. Most thermal reactors use enriched uranium with a level of enrichment of, typically, about 3%; the major exceptions are the Magnox reactors and the pressurized heavy-water-cooled and heavy-water-moderated reactors (HWRs), which use natural uranium. Uranium is converted to uranium hexafluoride before being enriched, generally in gaseous diffusion or centrifuge plants. Most enrichment was historically undertaken by gaseous diffusion, but increasingly the centrifuge process is being used because of its much lower cost; laser enrichment is currently under development and may make a significant contribution to the annual supply of enriched material by the end of the century. At present most enrichment services come from five suppliers:

Department of Energy (United States), Eurodif (France), Techsnabexport (Russian Federation), Urenco (Germany, Netherlands and the United Kingdom) and China. The enrichment capacity of these and a few other small producers was projected to be about 40 million separative work units (MSWU) in 1990 [14] compared with a demand for about 26 MSWU. After enrichment the uranium is reconverted into a form, generally an oxide, appropriate for fuel fabrication. The depleted uranium, or tails, from the enrichment process are generally stored pending decisions on their future use (e.g. in a fast reactor fuel cycle, further enrichment later or disposal). Occupational exposures occur during both the conversion stages and enrichment. Consideration here is limited to exposures during enrichment.

81. Occupational exposures to workers employed in the enrichment of uranium in six countries are summarized in Table 5. With two exceptions the data are for enrichment by the diffusion process; the exceptions are South Africa, where the jet nozzle process is used, and one of the two entries for the United Kingdom, which is for centrifuge enrichment. Sums or averages of reported data are given in Table 5; however, because of incomplete data on the separative work used in uranium enrichment, an extrapolation based on size of the practice to estimate worldwide doses cannot be applied. The alternative extrapolation, based on gross national product, is also inappropriate in this case, because enrichment is carried out in only a very few countries. In these circumstances, only an approximate estimate of worldwide doses can be made.

82. The annual effective dose to monitored workers, averaged over five-year periods and over all reported data, decreased progressively, from about 0.5 mSv in the first period to about 0.1 mSv in the third. The annual collective effective dose, averaged similarly, also decreased progressively, from about 5 man Sv in the first period to about 0.8 man Sv in the second and 0.4 man Sv in the third; these trends largely reflect trends in the United States, which contributes by far the greater part of the reported collective dose. These doses are from external irradiation. Although the potential exists for internal exposure in enrichment plants, its contribution was reported as negligible in comparison with external irradiation by those few countries reporting data on this aspect. In all countries reporting data, the distribution ratios are all zero, reflecting the relatively low levels of exposure encountered in enrichment compared with other stages of the fuel cycle.

83. Only the United Kingdom has reported data on separative work for enrichment by both the diffusion and centrifuge processes. These data provide the only reliable basis on which to estimate normalized collective doses from enrichment. For enrichment by diffusion, the normalized collective dose was about 0.5 man Sv $MSWU^{-1}$ [0.07 man Sv $(GW\ a)^{-1}$]; a comparable dose was experienced in the early stages of centrifuge enrichment, but this has since been reduced greatly to about 0.04 man Sv $MSWU^{-1}$ [0.005 man Sv $(GW\ a)^{-1}$] in the most recent five-year period. The use of much larger centrifuges and the greater throughput of enriched material with time have been the main contributors to these decreases. The normalized collective doses, in terms of energy generated, were estimated assuming that 0.13 MSWU were required to enrich the uranium needed to generate 1 GW a of electrical energy in a light-water-cooled, light-water moderated reactor (LWR).

84. The sums of the reported collective doses (and the average individual doses) in Table 5 are assumed, in the absence of better data, to be representative of worldwide exposures from the enrichment of uranium for use in the commercial nuclear fuel cycle. These data do not include contributions from several countries, most notably China and the former USSR; any underestimate resulting from this omission is, however, likely to be small compared with the overestimate resulting from the fact that the United States data include exposures arising during the enrichment of uranium for both civilian and defence purposes.

85. To estimate the normalized dose that is representative of this stage of the fuel cycle, it is assumed that the reported collective doses in 1975-1989 can be associated with the enrichment of that quantity of uranium needed for the generation of electrical energy by LWRs worldwide during the same period. Based on this assumption, the normalized collective dose, averaged over the whole period, is about 0.17 man Sv $MSWU^{-1}$ [0.022 man Sv $(GW\ a)^{-1}$]; this is broadly comparable with experience in the United Kingdom for enrichment by the diffusion process. In practice, because a fraction of the reported doses is likely to have arisen during the enrichment of uranium used in defence, the normalized collective dose is likely to be an overestimate.

86. In summary, the individual and collective doses from enrichment are small. Consequently, notwithstanding the major uncertainties in estimating worldwide exposures from this source, they will have little impact on the reliability of the estimated exposure from the whole of the nuclear fuel cycle.

C. FUEL FABRICATION

87. Many types of fuel are fabricated according to the reactor type in which they are used. The characteristics of fuels that are relevant here are the degree of

enrichment and the form, either metallic or oxide. The great majority of reactors use low enriched (typically a few per cent) uranium oxide fuel; the main exceptions are Magnox reactors, which use unenriched metal fuel, and HWRs, which use unenriched oxide fuel. The characteristics of the fuel and the reactor environment in which it is used influence the amount of energy that can be extracted from it per unit mass, and significant differences are to be expected between the various types of fuel. About 95% of fuel is currently fabricated for use in water-cooled reactors of various types, with about 85% for use in LWRs. The capacity for water reactor fuel fabrication in 1990 was estimated to be about 13 kt uranium, and the expected requirement for fuel was about 9 kt [I4].

88. The exposures from fuel fabrication have, in previous UNSCEAR Reports, been considered together with those from uranium enrichment. In this Annex they are evaluated separately in order to provide estimates of the doses arising at each main stage of the fuel cycle. Separate estimates are also made in this Annex for each of the main types of fuel. The purpose of this is to enable more realistic estimates to be derived of the normalized collective dose per unit energy generated for the different fuel cycles based on the various reactor types. The four types of uranium fuel to be considered are unenriched metal fuel, used in Magnox reactors; low enriched oxide fuel, used in advanced gas-cooled, graphite-moderated reactors (AGRs) and in LWRs; unenriched oxide fuel, used in HWRs; and mixed oxide fuels, used in fast breeder reactors (FBRs). Mixed oxide fuels (uranium-plutonium) are increasingly being developed for use in LWRs, but occupational exposures arising during their fabrication have yet to be reported.

89. There are two main sources of exposure in the fabrication of uranium fuels: external exposure to gamma-radiation emitted by the uranium isotopes of concern and their decay products and internal exposure from the inhalation of uranium and its decay products. The relative importance of these two routes of exposure varies with the type of fuel fabricated and the manufacturing process. Data reported from the United Kingdom, where significant resources have been allocated to limit internal exposure, indicate that external exposure is the major source; this, however, may not always be so. Individual monitoring for internal exposure, with formal entry of the results in dose records, is usually carried out for only a fraction of the workforce; monitoring of the working environment is often sufficient.

90. Occupational exposures to workers employed in the fabrication of each type of uranium fuel are summarized in Table 6. The number of monitored workers and the annual collective and individual doses, all averaged over successive five-year periods, are illustrated in Figure III for each fuel type. The normalized collective effective doses and the dose distribution ratios are illustrated in Figure IV.

91. *LWR fuel.* LWR fuel is fabricated in several countries and is used in pressurized light-water-moderated, light-water-cooled reactors (PWRs) and in boiling light-water-moderated, light-water-cooled reactors (BWRs). The fuel is uranium oxide with an average enrichment of about 3% and is clad in a zirconium alloy. Mixed oxide (uranium and plutonium) fuels are being fabricated for use in LWRs, but as their contribution is small and few occupational exposure data are available, they are not considered further. The normalized collective effective doses in Table 6 have been estimated assuming that 37 t of LWR fuel is needed, on average, to generate 1 GW a of electrical energy.

92. The data for LWR fuel are incomplete in two respects: first, no data have been obtained from some countries that are major fuel producers and, secondly, some of the reported data did not contain estimates of the amounts of fuel fabricated. Worldwide estimates of the annual collective dose and the number of monitored workers have been obtained by scaling the sum of reported data by the ratio of LWR 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 LWR fuel worldwide and in some of the major producing countries. Annual fuel production in these cases was assumed to be equal to that which would have been needed for the generation of electrical energy by LWRs in those particular countries or the world in that particular year. This approximation was used to estimate fuel production in the United States as well as worldwide. Because the United States also supplies fuel to other countries, the amounts predicted in this way are likely to be underestimates of actual production; the normalized collective doses given for the United States are, by the same token, likely to be overestimates. Similar degrees of under- or overestimation can be expected in the respective worldwide data owing to the major contribution made by the United States to the total fuel production.

93. The worldwide annual amounts of LWR fuel fabricated, averaged over five-year periods, increased from 1.6 kt to about 7.0 kt between the first and third periods. The average number of workers also increased in the same period, but by about 50%, a much smaller increase than in the amount of fuel produced. The worldwide annual effective dose to monitored workers, averaged over five-year periods, decreased progressively, from 1.7 mSv in the first

period to about 0.5 mSv in the third period. Notwithstanding the fourfold increase in fuel produced, the worldwide annual collective dose decreased, from 29 to 11 man Sv. These changes are reflected in a decrease, by an order of magnitude, in the worldwide normalized collective effective dose over the same period, from 18 to 1.6 man Sv kt^{-1} [0.7-0.07 man Sv $(GW\ a)^{-1}$]. The average fraction of the workforce receiving annual doses in excess of 15 mSv, NR_{15}, declined over the period, from 0.013 to 0.0003; the corresponding fraction of the collective dose arising from individual doses in excess of that level, SR_{15}, decreased, from about 0.4 to 0.02.

94. The data for individual countries and their trends with time vary considerably about the average worldwide values. Because of the major contribution made by the United States to worldwide fuel production, the doses for that country are broadly comparable with the worldwide averages, albeit slightly greater in general. The average annual doses to monitored workers in other countries are, in general, smaller than the worldwide averages, often by a significant factor. In Japan, the normalized collective doses are substantially less than the worldwide averages, particularly in earlier times; the values in other countries are broadly comparable with the worldwide averages.

95. Only Spain and Japan have explicitly included the data on internal exposures. In Spain, the annual contribution of internal exposure reported since 1988 varied from 20% to 40%; its explicit inclusion may be one reason why the doses in Spain are, in general, greater than those reported elsewhere. In the absence of further information, the doses reported for those countries not explicitly including internal exposures must be considered to be underestimates by indeterminate amounts. Data on the contribution of internal exposure to the doses in fuel fabrication are an essential requirement if valid comparisons are to be made. The potential importance of neglecting internal exposures can be gauged from a review by the National Council on Radiation Protection and Measurements (NCRP) of occupational exposure in the United States [N1]. In that review it was suggested that when account was taken of internal exposures, the average effective dose to fuel fabrication workers in the United States would increase (from a level of about 1.3 mSv for measurably exposed workers for external exposure alone) to a level comparable with that experienced by nuclear power plant personnel (see Section II.D).

96. ***HWR fuel.*** Fuel for HWRs is fabricated in Argentina, Canada, India and the Republic of Korea, which are the main countries where this reactor type is used. The total of the reported data can, therefore, be assumed to be representative of worldwide exposure arising from the fabrication of this fuel type. The fuel is unenriched uranium oxide. The normalized collective effective doses in Table 6 have been estimated assuming that 180 t of HWR fuel is needed, on average, to generate 1 GW a of electrical energy, except when more specific data on equivalent energy generation were provided in response to the UNSCEAR Survey on Occupational Exposures.

97. The worldwide annual production of fuel, averaged over five-year periods, increased progressively, from about 0.6 kt (about 3 GW a equivalent) in the first period to about 1.6 kt (about 9 GW a equivalent) in the third period. By far the greater part (about 95% averaged over the whole period) of the fuel was fabricated in Canada. The worldwide number of monitored workers has increased over the three periods, from about 500 to about 1,100. The worldwide average effective dose to monitored workers, which was about 1.3 mSv in the first period, declined to about 1 mSv in the second but increased to about 1.7 mSv in the third period. The same doses in Canada increased progressively over this time, from about 1.3 mSv to about 2.4 mSv, with most of the increase occurring in 1985-1989; some of this increase may be attributable to increasing fuel production with a decreasing workforce (at least a monitored workforce). The average doses in the other countries are, in general, less than the worldwide averages. The contribution of internal exposure is not significant; these exposures are included only in Canada and are reported to be negligible. Doses to measurably exposed workers have been reported for three of the countries and are significantly greater than those to monitored workers. The annual dose to measurably exposed workers in Canada, averaged over five-year periods, increased progressively, from about 2 to about 3.6 mSv (i.e. doses were about 50% greater than those to monitored workers).

98. The worldwide annual collective effective dose, averaged over five-year periods, increased from about 0.7 man Sv to about 1.9 man Sv. The worldwide average normalized collective dose decreased from about 1.1 to about 0.9 man Sv kt^{-1} [0.2-0.16 man Sv $(GW\ a)^{-1}$] between the first two periods but increased in the third period to about 1.2 man Sv kt^{-1} [0.22 man Sv $(GW\ a)^{-1}$]. During those 15 years, the normalized dose in Canada decreased progressively from about 1.1 to about 0.7 man Sv kt^{-1} [0.2-0.13 man Sv $(GW\ a)^{-1}$]. The worldwide normalized dose increased in the last five-year period, because much higher than average normalized doses arose during fuel fabrication in India. Significant variation is apparent in the distribution ratios between countries but, in general, the values are small. The fraction of the worldwide workforce receiving annual doses in excess of 15 mSv was about 0.003, averaged over all three periods, with

a significantly lower value in 1980-1984. The fraction of the worldwide collective dose arising from annual doses in excess of the same level was about 0.005, averaged over the same period, again with a much lower value in 1980-1984.

99. *Magnox fuel.* Magnox fuel is fabricated mainly in the United Kingdom and is used there and in Japan and Italy in this reactor type. The fuel is natural uranium clad in a Magnox alloy. Metal fuel was also fabricated in France for use in gas-cooled, graphite-moderated reactors (GCR)s in that country. The normalized collective effective doses in Table 6 have been estimated assuming that 330 t of Magnox fuel is needed on average to generate 1 GW a of electrical energy. In the absence of reported data from France, the data for Magnox fuel fabricated in the United Kingdom are assumed to be representative of worldwide levels.

100. The annual amount of fuel fabricated, averaged over five-year periods, remained relatively constant with time at about 850 t. The number of workers has increased from about 900 to about 1,100 over the same period. The annual normalized collective effective dose, averaged over successive five-year periods, increased from about 2 man Sv kt^{-1} [0.7 man Sv $(GW\ a)^{-1}$] in the first period to about 4.3 man Sv kt^{-1} [1.4 man Sv $(GW\ a)^{-1}$] in the last. This increase is largely due to the inclusion, since 1986, of internal exposures in the reported data. The average contribution of internal exposure to the total exposure in 1986-1990 was about 35%; the doses reported for years before 1986 are underestimates by at least a comparable amount and need to be adjusted accordingly. Because of this underestimation in earlier years, the increase with time in the normalized collective doses is more apparent than real.

101. The average annual effective dose to the monitored workforce has varied considerably from year to year but with some indication of a declining trend. The annual dose from external exposure alone was about 2 mSv in the period 1985-1989; taking into account of internal exposure, the average annual dose in the period can be estimated to have been about 3 mSv. The fraction of the workforce receiving annual doses in excess of 15 mSv was low, about 0.002 over the first two five-year periods. Because no account was taken of internal exposure during this period, these values are doubtless underestimates. In 1986, when internal exposure was first included, the fraction increased significantly, to about 0.04 (about 0.018 averaged over the five-year period) but thereafter declined to essentially zero.

102. *AGR fuel.* AGR fuel is fabricated only in the United Kingdom and used in reactors there; the reported data can, therefore, be taken as the worldwide level for this type of fuel. The fuel is uranium oxide with an average enrichment of about 2.7% and is clad in stainless steel. The data in Table 6 are predominantly for the fabrication of AGR fuel but include a small component (about 10%) of PWR fuel. The simplifying assumption is made here that the data are solely for AGR fuel, and the normalized collective effective doses have been estimated on the basis that 38 t of AGR fuel is needed, on average, to generate 1 GW a of electrical energy. The data also include the workforce involved in, and the collective dose arising from, fuel fabrication and conversion (and reconversion) of uranium to uranium hexafluoride for enrichment. Only about 5% of the collective dose is attributable to the conversion processes; data are not, however, available on the size of the respective workforces to enable the combined data to be presented separately for conversion and fabrication. The average individual doses to workers involved in conversion and fabrication are, however, similar.

103. The annual amount of fuel produced, averaged over five-year periods, remained relatively constant, at about 400 t. Over the whole period, the number of monitored workers, averaged about 1,800, with evidence of a small increase in the two later five-year periods. The normalized collective effective dose, averaged over five-year periods, changed little between the first two periods and was about 8 man Sv kt^{-1} [0.3 man Sv $(GW\ a)^{-1}$]. In the third period it increased to about 12 man Sv kt^{-1} [0.45 man Sv $(GW\ a)^{-1}$]. Much of this increase may be more apparent than real for the reasons set out above in connection with Magnox fuel, in particular the inclusion of internal exposures in the reported data from 1986 onwards. The contribution from internal exposure was about 35% averaged over the period 1986-1990; accordingly, the doses reported before 1986 are likely to be underestimates by a similar or greater factor and need to be adjusted accordingly.

104. The average annual effective dose to monitored workers varied considerably from year to year, with a slight decline being noticeable. The average annual dose (external exposure only) in the first five-year period declined from about 2.3 to about 2 mSv in the second; to take account of the contribution of internal exposure, these doses should be increased by 30% or more. In the last five-year period the average annual dose (external exposure only) remained about 2 mSv, with a total dose (internal and external exposures) of about 3 mSv. The fraction of the workforce receiving annual doses in excess of 15 mSv was low, about 0.001 over the first two five-year periods. Because no account was taken of internal exposure during this period, these values are doubtless underestimates. In 1986, when internal exposure was first included, the

fraction increased significantly to about 0.05 (about 0.014 averaged over the five-year period) but thereafter declined to essentially zero.

105. *FBR fuel.* Data on FBR fuel fabrication have been reported only from Japan and are insufficient to make a reliable estimate of worldwide dose from this type of fuel. It can be noted, however, that the average individual doses are broadly comparable with those arising in Japan during the fabrication of LWR fuel. The normalized collective doses per unit mass of fuel fabricated are, however, very much greater; this difference would decrease if the doses were normalized in terms of potential energy generation, owing to the much greater burn-up achieved by FBR fuels. One probable contributor to the larger normalized doses is the small or pilot scale of fuel production.

106. *Summary.* Worldwide exposures from fuel fabrication are summarized in Table 7. The annual amount of fuel fabricated worldwide, averaged over five-year periods, increased threefold (in terms of potential energy that could be generated from it) over the period of interest, during which the monitored workforce has increased by about 40%. Notwithstanding this increase in production, the worldwide annual collective dose has decreased, from 36 to 22 man Sv; an even more striking decrease occurred in the normalized collective dose, from about 0.6 man Sv $(GW\ a)^{-1}$ to about 0.1 man Sv $(GW\ a)^{-1}$. A decrease by a factor of more than 2 occurred in the average dose to monitored workers. The data on distribution ratios are somewhat less complete than those for other statistics of interest. Notwithstanding this, the available data overall indicate a generally downward trend with the ratio NR_{15} decreasing more than a factor of 5 from about 0.01 in the first period to 0.002 in the third; over the same period the ratio SR_{15} decreased by a factor of 20 from about 0.4 to about 0.02.

107. Most of the fuel fabricated was for use in LWRs. About 80% of the total collective dose arose from the fabrication of LWR fuel in the first five-year period; this contribution decreased to about 50% in the latest period, with about 40% from GCR fuel and about 10% from HWR fuel. The normalized collective dose (expressed in terms of potential energy that could be generated by the fuel) is significantly greater for Magnox than for other fuels; the much lower burn-up achieved by Magnox fuel is perhaps the main reason for this difference. Somewhat greater individual doses (approaching a factor of two when averaged over the whole period) are associated with both types of GCR fuel compared with fuel for other reactor types. Some of these comparisons need qualification, however, because internal exposures were not, in general, included in the data reported for LWR fuels. As a consequence, some of the differences between GCR and LWR fuels that are identified here may be more apparent than real. Better quantification is needed of the contribution of internal exposure in LWR fuel fabrication; pending this, the data reported here for this fuel type must be regarded as underestimates.

D. REACTOR OPERATION

108. Within the nuclear fuel cycle, reactors are the most common facility. About 430 reactors were in operation at the end of the 1980s. Consequently, there are more occupational data for reactors than for any other type of nuclear installation. Several reactor types have been developed to the commercial stage, in particular PWRs, BWRs, GCRs (comprising, among others, Magnox and AGRs), HWRs and light-water-cooled, graphite-moderated reactors (LWGRs). Detailed consideration is given to each of these with more limited consideration of liquid metal fast breeder reactors (FBRs) and high-temperature gas-cooled, graphite-moderated reactors (HTGRs), which are still largely at a prototype stage of development.

109. Data on occupational exposures at reactors of each type are summarized in Table 8. Worldwide levels of exposure have been estimated from reported data; the extrapolation is based on the total energy generated by the reactor type relative to the energy generated in countries reporting data. The degree of extrapolation necessary was small, as the reported data were substantially complete (about 90% for PWRs and BWRs, 95% for HWRs, 80% for GCRs and 70% for FBRs).

110. The annual data reported in response to the UNSCEAR Survey of Occupational Exposures have been averaged over five-year periods and only the average values are given in Table 8. The variations in annual values are presented in Figures V and VI to illustrate temporal trends in more detail. Data, where available, are also presented on the main activities that give rise to occupational exposures in the different reactor types and on typical levels of dose that occur when undertaking a number of common tasks.

111. Since relatively few data are available on average doses to measurably exposed workers compared with those to the monitored workers, no attempt has been made to estimate a worldwide average dose. The data that are available indicate that the average dose to measurably exposed workers is typically up to about twice that for the monitored workforce, although there is much variation between countries and with time (see Table 8). More data on average doses to measurably exposed workers would be useful; for the reasons previously identified, comparisons made in these terms would, in general, be more reliable than those made on the basis of the dose to monitored workers.

112. Several factors have influenced the trends in reported exposures. These include the commissioning of a large number of new PWRs in the early 1980s, the lower annual collective doses achieved in new reactors because of additional and improved design provisions, and the large reductions in dose achieved in reactors in the United States once the safety modifications required after the accident at Three Mile Island had been completed. Significant reductions in doses in existing reactors have also been achieved, in particular from the greater attention given to reducing circuit activity levels, the reduction of unscheduled maintenance and the greater emphasis on keeping doses "as low as reasonably achievable" (ALARA).

113. Considerable improvements have taken place in the recording and documentation of occupational exposures in recent years, and the creation of national and international databases has greatly facilitated the reliable extraction of relevant statistics. The use of information from these databases will inevitably lead to some, albeit small, differences between the statistics presented in this Annex and those given in earlier UNSCEAR Reports for the same time periods, but an overriding aim is to treat all data included in a consistent manner.

114. 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. Four more specific observations need to be made in the present context. First, differences exist in the protocols adopted in various countries as to 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.

115. Secondly, the procedures for the recording and inclusion of doses received by transient or contract workers may differ between utilities and between countries, 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 (as opposed, ideally, to only once, 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 in those cases where extensive use is made of transient workers.

116. Thirdly, different approaches are apparent between countries 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, reported data have been modified to enable them to be fairly compared with other data; these changes are indicated in the respective Tables. Attention is also drawn to any unmodified data for which doubts may exist on whether or to what extent they can be compared fairly with the other data.

117. Fourthly, no undue significance should be attached to normalized collective doses that have been derived on the basis of a small number of reactors operating for a short period. Because much of the exposure arises from maintenance carried out during periodic reactor shutdowns, the normalized doses (and particularly those normalized in terms of energy generated) are useful only when derived as an average of a large number of reactors or over a long operating period.

1. Light-water reactors

118. LWRs comprise by far the majority of the installed nuclear generating capacity. About 70% of them are PWRs and about 30% are BWRs. About 40% the LWRs are installed in the United States and about 20% in France, with the remainder distributed among some 20 countries. With respect to occupational exposures, experience has shown significant differences at PWRs and BWRs. Each type is therefore considered separately.

(a) Average annual doses

119. *PWRs.* 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. In general, the contribution of neutrons to the overall level of external exposure is

insignificant. Most occupational exposures occur during scheduled plant shut-downs, 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; significant changes have occurred with time in many of these areas, which have affected the levels of exposure.

120. The worldwide installed capacity of PWRs, averaged over five-year periods, increased from about 50 GW in 1975-1979 to about 180 GW in 1985-1989; the corresponding increase in the average annual energy generated worldwide was somewhat greater, from about 30 to 120 GW a. On average, 40% of this energy was generated by PWRs in the United States and about 20% in France. The number of monitored workers in PWRs worldwide has increased from about 60,000 to about 230,000 over the period (Figure V). The average annual collective effective dose increased by a factor of about 2 (from about 220 to about 450 man Sv) between the first two five-year periods; the increase in the third period to about 500 man Sv was small when compared with the doubling of energy generated in the same period. The normalized collective dose changed little over the first two five-year periods, when it was about 8 man Sv $(GW\ a)^{-1}$; in the third period it decreased substantially, to about 4 man Sv $(GW\ a)^{-1}$ (Figure VI).

121. The annual effective dose to monitored workers, averaged over five-year periods, fell from about 3.5 mSv in the first period to about 2.2 mSv in the third; most of this decrease occurred between the second and third periods. The fraction of the monitored workforce receiving annual doses in excess of 15 mSv decreased progressively, falling from about 0.09 to about 0.03 over the entire period; the corresponding decrease in the fraction of the collective effective dose arising from annual doses in excess of the same level was from about 0.6 to about 0.3. These fractions were estimated from a smaller set of data than was used to estimate doses, as not all countries reported these quantities.

122. There are considerable variations about the worldwide average values in both the trends and levels of dose in individual countries. Average values of individual and normalized collective dose are illustrated in Figure VII for geographical groupings. The regions are Asia, Eastern Europe (including the former USSR), Western Europe and the United States. The normalized collective doses in Western European and Asian reactors are generally significantly lower than the worldwide averages, while those in the United States and Eastern European reactors are higher than the average. The variations in the average individual doses to monitored workers about the average values are less pronounced: only in Asian reactors are the doses consistently less than the average. Considerable variation between countries remains, however, even within these narrower regional groupings (e.g. in Eastern Europe the normalized collective doses in Czechoslovakia and in Hungary were, on average, less by a factor of about 5 than those in the German Democratic Republic and the former USSR).

123. The largest normalized collective effective doses occurred at PWRs in the German Democratic Republic, Spain, the former USSR and United States; in Czechoslovakia, Finland, France, Hungary, South Africa and Sweden, the normalized doses were consistently and significantly less than the worldwide averages. These differences in normalized collective doses are largely, but not entirely, reflected in differences between the average individual doses in the respective countries. Downward trends are apparent in the normalized doses in most countries, in particular between the second and third five-year period; the decrease was most pronounced for the Federal Republic of Germany, Japan, the Republic of Korea, Spain, Sweden, the former USSR and the United States. The data for France show an upward trend, having increased by about 20% over the period; the absolute level of the normalized collective dose is, however, still lower than the average for PWRs overall. A few countries that only recently introduced reactors for generating electrical energy [e.g. South Africa and China (Taiwan)] exhibit comparatively low, albeit increasing, normalized collective doses; this is typical of the trends experienced elsewhere.

124. Variations in the doses between reactors within a country are also of interest. Data for PWRs in the United States are illustrated in Figure VIII, in particular the median, the 25th and 75th percentiles and the minimum and maximum values of the collective effective dose per reactor. A wide range of variation is evident and is to be expected, given that much of the exposure arises during repair and maintenance activities and while making safety modifications, all of which are carried out periodically and at different times and to different degrees on each reactor. The various statistics, however, show the same general trends indicated in Table 8 for the normalized collective effective doses averaged over all PWRs in the United States, in particular the higher doses in the first half of the 1980s, which resulted from safety modifications made in response to the accident at Three Mile Island.

125. *BWRs.* External irradiation is also the major 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.

126. The worldwide installed capacity of BWRs, averaged over five-year periods, increased from about 29 GW in 1975-1979 to about 67 GW in 1985-1989; the corresponding increase in the average annual energy generated worldwide was somewhat greater, from about 15 to 42 GW a. On average, 40% of this energy was generated by BWRs in the United States and 25% in Japan. The number of monitored workers in BWRs worldwide increased from about 60,000 to about 140,000 over the period (Figure V). 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 period, to about 330 man Sv, notwithstanding an increase by more than 60% in the energy generated over the same period. The normalized collective dose, averaged over five-year periods, changed little over the first two periods and was about 18 man Sv $(GW\ a)^{-1}$; in the third period it decreased substantially, to about 8 man Sv $(GW\ a)^{-1}$ (Figure VI).

127. The annual effective dose to monitored workers, averaged over five-year periods, fell from about 4.7 mSv in the first period to about 2.4 mSv in the third; most of this decrease occurred between the second and third periods. The fraction of the monitored workforce receiving annual doses in excess of 15 mSv increased from about 0.07 to about 0.08 between the first two five-year periods and decreased subsequently to about 0.03 in the third period; the fraction of the collective effective dose arising from annual doses in excess of 15 mSv was about 0.6 in each of the first two five-year periods, decreasing to about 0.4 in the third period. These fractions were estimated from a smaller set of data than used to estimate doses, as not all countries reported these quantities.

128. There are considerable variations about the worldwide average values in both the trends and levels of dose in individual countries. Some regional variations are illustrated in Figure VII. The normalized collective doses in Western Europe are significantly less than those elsewhere and are typically smaller by a factor of about 2 than the worldwide averages over the whole period. Those in the United States are, apart from the first period, some three to four times greater than those in Western Europe. For BWRs in Japan and China (Taiwan), the normalized dose, averaged over both countries, in the first period was about twice the worldwide average, but in subsequent periods it was less than the average. The variations in the average annual individual doses to monitored workers exhibit trends similar to those for the normalized doses, but the magnitude of the variations about the average are much smaller.

129. Normalized collective effective doses that are consistently and significantly less than the worldwide averages were reported for BWRs in Finland and Sweden. The largest normalized collective doses occurred in India and were about a factor of 10 greater than the worldwide averages for the corresponding periods. Relatively large normalized doses also occurred in the Netherlands, but these data should not be given undue significance, as they apply only to one small reactor. In most other countries there is considerable variation in the normalized doses about the average values, with little evidence of consistent trends between respective time periods. These differences in normalized collective doses are largely, but not completely, reflected in differences between the average individual doses in the respective countries. Major downward trends with time are apparent in the normalized doses in most countries, in particular between the second and third five-year period analysed; the decrease was most pronounced for the Federal Republic of Germany, Japan, Spain and the United States. In the United States there was a large increase in the normalized collective dose in the second period; the safety modifications made in response to the accident at Three Mile Island were the main reason for this increase. The trend in collective dose per reactor to workers at BWRs in the United States is illustrated in Figure VIII. The wide range of variation between reactors is, in general, greater than the variation for PWRs.

(b) Dose distribution ratios for LWRs

130. Comprehensive statistics have been compiled in the United States on the distributions of individual doses making up the collective effective doses [B2, B4]. These enable reliable estimates to be made of the collective dose distribution ratio, SR, and also of the fraction of the workforce exposed above any prescribed level of individual dose, NR. In Figure IX the distribution ratios NR_E and SR_E are given for selected years as a function of the annual effective dose, E. These distributions are summarized in Table 9. Large reductions with time are evident in the fraction of measurably exposed workers receiving an annual effective dose in excess of 15 mSv. Between 1973 and 1989, this fraction, NR_{15}, decreased from 0.24 to 0.03, with much of the reduction occurring in the 1980s. Over the same period there was a 60-fold decrease (from 0.06 to 0.001) in the fraction of workers exposed to annual doses in excess of 30 mSv, a threefold decrease (from 0.34 to 0.09) in those exposed in

excess of 10 mSv, and a twofold decrease (from 0.43 to 0.22) in those exposed in excess of 5 mSv.

131. The reductions in the percentages of the collective effective dose arising from individual annual doses in excess of particular values are also substantial. The fraction of the collective dose arising from annual individual doses in excess of 15 mSv has decreased fourfold (from 0.71 to 0.19) over the period 1973-1989. Over the same period there was a 30-fold decrease (from 0.30 to 0.009) from annual doses in excess of 30 mSv, a twofold decrease (from 0.85 to 0.43) from doses in excess of 10 mSv and a reduction by a factor of about 1.3 (from 0.93 to 0.70) from annual doses in excess of 5 mSv.

(c) Doses for specific tasks and occupational subgroups

132. Detailed statistics are gathered by the United States Nuclear Regulatory Commission on the collective dose for several general categories of work, job functions and types of personnel [B2, B4, R2]. The distribution of the collective dose between various work functions is shown in Figure X for LWRs during 1975-1989. By far the greater part of the collective dose arises in routine and special maintenance, with the contribution of other categories being small by comparison. Throughout the early 1980s, the contribution of special maintenance was greatest, a consequence of the safety-related modifications made after the accident at Three Mile Island. In the most recent period, the collective dose from routine maintenance exceeded that from special maintenance.

133. The distributions of doses between contract workers and utility personnel for separate work functions at LWRs in the United States [B2] has also been analysed. Most of the collective dose is received by contract worker personnel, in particular during special maintenance. Overall, the collective dose to contract workers is greater by a factor of about 2 than that to utility workers. Data reported for some other countries using LWRs (in particular Finland, France, the German Democratic Republic, the Federal Republic of Germany, Spain and Switzerland) show that contract workers typically receive 60%-90% of the total collective dose [L2].

134. The distribution of collective doses among five occupational groups, averaged over 1987-1989, is summarized in Table 10 for workers at LWRs in the United States. Most of the dose is received by maintenance personnel (66%). The largest individual doses are also received by maintenance personnel (about 30% greater than the average to workers in all other occupational groups), but those to health physicists are of a comparable magnitude.

2. Heavy-water reactors

135. HWRs are used in several countries but most extensively in Canada, where the CANDU reactor was developed and since 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.

136. The worldwide installed capacity of HWRs, averaged over five-year periods, increased from 5 GW in 1975-1979 to 14 GW in 1985-1989; the corresponding increase in the average annual energy generated worldwide was somewhat greater, from about 3 to 10 GW a. On average, 85% of this energy was generated by HWRs in Canada. The number of monitored workers in HWRs worldwide increased from about 7,000 to about 18,000 over the period. 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. 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%. The normalized collective dose decreased from about 20 to about 8 man Sv $(GW\ a)^{-1}$ between 1975 and 1979 and increased again to about 16 man Sv $(GW\ a)^{-1}$ in 1982 (Figure VI); subsequently the dose decreased to about 6 man Sv on average over the remainder of the 1980s. Averaged over five-year periods, the normalized collective dose was 11 man Sv $(GW\ a)^{-1}$ in the first period, decreasing to 8 man Sv $(GW\ a)^{-1}$ in the second period and to about 6 man Sv $(GW\ a)^{-1}$ in the third.

137. The annual effective dose to monitored workers worldwide showed similar variations, but averaged over five-year periods, it has decreased from 4.8 mSv in the first period to an average of 3.3 mSv over the second and third periods. Data on the average annual effective dose to measurably exposed workers are less complete than other data. The average dose to such workers exceeded that for monitored workers by factors ranging up to about 3, with considerable variation between countries. The fraction of the worldwide monitored workforce receiving annual doses in excess of 15 mSv decreased from 0.12 in the first period to about 0.07 in each of the following periods; the corresponding decrease in the fraction of the collective effective dose arising from annual doses in excess of that level was from about 0.7 to about 0.5. Both fractions show considerable variations from year

to year (Figure VI). They were estimated from a smaller set of data than was used to estimate doses, as not all countries reported this data.

138. There is wide variation in both the trends and levels of the doses in individual countries. In the first period the greater part (about 75%) of the worldwide collective dose occurred in Canada; averaged over the last two periods about 42% of the collective dose occurred in India with about 34% in Canada. The normalized collective dose in Canada was considerably less than the worldwide average, declining progressively from about 10 to about 2 man Sv $(GW\ a)^{-1}$ over the three periods. In Argentina and India the normalized doses have exceeded the worldwide averages and in India substantially so [about 80 man Sv $(GW\ a)^{-1}$, averaged over the period 1980-1989]. The decrease in the average annual individual dose to monitored workers in Canada was far greater than that of the worldwide average, decreasing from about 4.2 to 1.5 mSv over the period (over the same time the average dose to measurably exposed workers decreased from about 9 to about 4 mSv). The annual doses to monitored workers, averaged over the whole periods for which data were reported, were about 11 mSv in Argentina and about 6 mSv in India with considerable year to year variation about these average values.

3. Gas-cooled reactors

139. There are three main types of GCRs: Magnox reactors, including those with steel pressure vessels (SPVs) and those with prestressed concrete pressure vessels (CPVs); advanced gas-cooled reactors (AGRs); and high-temperature gas-cooled reactors (HTGRs). Only the Magnox and AGRs have, as yet, reached commercial application; HTGRs exist only in prototype forms. Most of the experience with GCRs has been obtained in the United Kingdom, where they have been installed and operated for many years. Initially, all GCRs were of the Magnox type; 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.

140. ***Magnox and AGRs.*** In previous UNSCEAR Reports the data for Magnox reactors and AGRs have been combined, despite potentially large differences in both the individual and normalized collective effective dose for these reactor types (and also between Magnox reactors with different types of pressure vessel). These differences arise mainly from the use of concrete as opposed to steel pressure vessels in AGRs (and in the later Magnox reactors) and the increased shielding that they provide against external radiation, the dominant source of occupational exposure from this reactor type. In this Annex separate estimates are made for each reactor type.

141. The worldwide installed capacity of GCRs, averaged over five-year periods, increased from about 9 GW in 1975-1979 to about 13 GW in 1985-1989; the corresponding increase in the average annual energy generated worldwide was comparable, from about 5 to 7 GW a. On average, 75% of this energy was generated by GCRs in the United Kingdom. The number of monitored workers in GCRs increased worldwide from about 13,000 to 31,000 over the period. The average annual collective effective dose decreased from 36 man Sv in the first five-year period to 24 man Sv in the third, with much of the decrease occurring between the last two periods. The normalized collective dose, averaged over five-year periods, decreased from about 7 to about 3 man Sv $(GW\ a)^{-1}$ over the period, with most of the decrease again occurring between the last two periods.

142. The annual effective dose to monitored workers worldwide, averaged over five-year periods, fell progressively from 2.8 mSv in the first period to about 0.8 mSv in the third. The fraction of the worldwide monitored workforce receiving annual doses in excess of 15 mSv is small: it decreased from 0.02 to 0.0002 over the period; the data are incomplete on the fraction of the collective effective dose arising from annual doses in excess of that level, but in the third period the fraction was 0.008. The substantial decreases in the average individual and normalized collective doses largely resulted from the gradual introduction of AGRs in the United Kingdom; the doses in these reactors are significantly lower than those in Magnox reactors, at least those with steel pressure vessels.

143. There are major differences in the occupational exposures at different types of GCRs. Data for different generations of Magnox reactors, in particular those with steel pressure vessels and those with concrete pressure vessels, and for AGRs are summarized in Table 11. A distinction is also drawn between exposures in the first-generation Magnox-SPV reactors constructed with the dual purpose of producing weapons-grade plutonium and electrical energy and those later built solely for the generation of electrical energy. The normalized collective effective doses, averaged over the whole period, varied considerably from about 30 man Sv $(GW\ a)^{-1}$ for first-generation Magnox-SPV reactors to about 1 man Sv $(GW\ a)^{-1}$ for both AGR and Magnox-CPV reactors; for second-generation Magnox-SPV reactors the dose was, on average, about 8 man Sv $(GW\ a)^{-1}$. Similar trends are evident in the annual individual doses. The average

annual dose to monitored workers in first-generation Magnox-SPV reactors has remained relatively uniform at about 8 mSv, whereas that in Magnox-CPV reactors declined from about 1 to 0.2 mSv over the period; the average annual dose in the second generation of Magnox-SPV reactors has declined over the same period from about 3 to about 1 mSv.

144. The scale of these differences demonstrates the importance of disaggregating occupational exposures reported for GCRs, in particular if the objective is to estimate normalized collective doses for fuel cycles based on different reactor types. Earlier estimates, based on combined data for GCRs, are largely representative of experience with Magnox-SPV reactors. Much lower doses occur during the operation of both Magnox-CPV reactors and AGRs.

145. ***HTGRs.*** A number of prototype HTGRs have been operated, but this reactor type has yet to be adopted for commercial operation. Occupational exposure data have been reported for only one of these reactors, Fort St. Vrain in the United States [R2]. These data are summarized in Table 8, but they are insufficient to estimate worldwide exposures from this reactor type; the contribution compared with other reactors would, however, be minimal. The data indicate that exposures in HTGRs would be much lower than those encountered in LWRs and about the same or less than those experienced in AGRs.

4. Light-water-cooled, graphite-moderated reactors

146. LWGRs were developed in the former USSR and have only been installed there. Occupational exposure data have been reported in [B11] for LWGRs, but the data are incomplete, both in terms of the number of reactors and the period over which they operated. Overall (worldwide) levels of exposure from this reactor type have been estimated by scaling the reported data to the total energy generated by LWGRs. Data on energy generation were largely obtained from information submitted [B11, I8, I9]; data for missing periods were estimated from the installed capacity and the average load factor for the years when data were available.

147. The worldwide installed capacity of LWGRs, averaged over five-year periods, increased from about 6 GW in 1975-1979 to about 15 GW in 1985-1989 (it should be noted that all doses quoted for the last period are averages over 1985-1987 because no data were available for 1988 and 1989); the corresponding increase in the average annual energy generated worldwide was comparable, from about 4 to 10 GW a. The number of monitored workers in LWGRs worldwide increased from about 5,000 to about 13,000 over this period. The average annual collective effective dose increased from about 36 man Sv in the first five-year period to about 170 man Sv in the third, with much of the increase occurring between the last two periods. The normalized collective dose, averaged over five-year periods, was comparable in the first two periods, about 8 man Sv $(GW\ a)^{-1}$, but doubled to about 17 man Sv $(GW\ a)^{-1}$ in the third period. The annual effective dose to monitored workers worldwide, averaged over five-year periods, was about 6 mSv in each of the first two periods, increasing to about 13 mSv in the third period. No data have been reported on the fraction of the monitored workforce receiving annual doses in excess of 15 mSv or on the fraction of the collective effective dose arising from annual doses in excess of that level.

148. The large increases in both the average individual and normalized collective doses in the third period resulted from the accident at Chernobyl. The effect of the accident on these doses is illustrated in Figures V and VI. In 1986, both the average annual individual and normalized collective doses increased by a factor of about 4 relative to those in the immediately preceding years. In 1987, both doses decreased by a factor of about 2; no data are currently available on how they varied in subsequent years. Increases in exposures were reported [B11] for Chernobyl and other LWGRs during 1986. For the other LWGRs the increases are largely artificial, at least in so far as they have been associated with a particular reactor (exposures received while undertaking temporary work at Chernobyl were included in the records at the LWGR where the workers were normally employed). It may be questioned whether the additional exposures received by operational staff at LWGRs generally (because of time spent at Chernobyl following the accident) should be included here, as opposed to being categorized under exposures from accidents. The doses attributed are, however, strictly limited to those received by operational staff and do not include the much larger collective doses received by those involved with mitigating the consequences of the accident and with subsequent clean-up operations. In this context the attribution is judged appropriate.

5. Fast breeder reactors

149. A number of prototype FBRs with a wide range of installed capacities have been developed and operated over the past three decades. It is unlikely, however, that this type of reactor will see significant commercial use, except possibly in a few countries, before the early decades of the next century. The less-than-expected growth in the use of nuclear energy, the

continuing relatively low cost of uranium and the economic risks of developing a complete fast reactor fuel cycle are the main factors delaying the commercial introduction of FBRs.

150. The worldwide installed capacity of FBRs, averaged over five-year periods, has increased from about 1 GW in 1980-1984 to about 2 GW in 1985-1989; over the same period the average annual energy generated worldwide increased from about 0.5 to about 0.7 GW a. The number of monitored workers in prototype FBRs worldwide is estimated to have increased from about 1,400 to about 2,000 between these two periods. The average annual collective effective dose increased from about 0.6 man Sv to about 1 man Sv during the same time. The normalized collective effective dose, averaged over five-year periods was broadly the same in both periods at about 1.3 man Sv $(GW\ a)^{-1}$. The annual effective dose to monitored workers worldwide, averaged over five-year periods, was about 0.5 mSv in both periods.

151. While these data need to be qualified because they apply specifically to prototype facilities, they do indicate that the levels of occupational exposure in FBRs are likely to be much lower than those experienced at reactors of most other types currently in commercial operation.

6. Summary

152. Data on occupational exposures at reactors worldwide are summarized in Table 12. The worldwide installed capacity of all reactors, averaged over five-year periods, increased from about 100 GW in 1975-1979 to 290 GW in 1985-1989; the increase over the corresponding period in the average annual energy generated was from 55 to about 190 GW a. Averaged over the whole period, about 80% of the total energy was generated in LWRs (of this, about 70% was from PWRs and 30% from BWRs), with contributions of about 7% each from HWRs, GCRs and LWGRs. The number of monitored workers increased from about 150 to 430 thousand over the same period.

153. The annual collective effective dose, averaged over five-year periods, increased from about 600 man Sv in the first five-year period to about 1,000 man Sv in the second, with a further increase to about 1,100 man Sv in the third. The trend in annual values is indicated in Figure V. About 80% of the collective dose occurred at LWRs, with broadly similar contributions from PWRs and BWRs. Averaged over the whole period the contribution of HWRs has been about 5%, that of GCRs about 3% and that of LWGRs about 10% (about 6% prior to the Chernobyl accident).

154. The normalized collective effective dose, averaged over all reactors, varied little before 1984, when it was about 11 man Sv $(GW\ a)^{-1}$; thereafter it declined steadily to about 5 man Sv $(GW\ a)^{-1}$ in 1989 (see Figure VI). A generally decreasing trend is apparent in the normalized collective doses for most reactor types. The values for PWRs, LWGRs (before the Chernobyl accident) and GCRs overall (values for AGRs and Magnox-CPV reactors are much smaller) are broadly comparable; the values for HWRs and BWRs are somewhat larger, the latter substantially so in the earlier years.

155. The annual effective dose to monitored workers, averaged over all reactors, fell steadily from more than 4 mSv in 1975 to about 2 mSv in 1989. With the exception of LWGRs, a downward trend is evident in the average annual dose in each reactor type. There are, however, considerable differences between reactors, both in the absolute magnitudes of these doses and in their rate of decline.

156. Data on the dose distribution ratios NR_{15} and SR_{15} are less complete than data for other quantities (e.g. no data for LWGRs, FBRs, HTGRs and incomplete data for other reactor types). Values of these ratios, averaged over all reported data, are given in Table 12. Until more complete data are obtained, these averages can only be said to be indicative of worldwide values. Averaging over all reported data, the fraction of monitored workers receiving annual effective doses in excess of 15 mSv was about 0.09 in 1975 decreasing to about 0.03 by 1989; over the same period the fraction of the collective dose, arising from annual doses in excess of the same level, decreased from about 0.6 to about 0.3.

E. FUEL REPROCESSING

1. Average annual doses

157. Spent irradiated fuel from nuclear reactors used to generate electrical energy was reprocessed on a commercial scale, for much of the 1970s and all of the 1980s, in only two countries, France and the United Kingdom. The facilities in those two countries have, however, also been used to reprocess irradiated fuel from other countries. In the United Kingdom only uranium metal fuel from Magnox reactors has to date been reprocessed on a commercial scale; a new plant for the reprocessing of oxide fuel is, however, scheduled to begin operation in the early 1990s. In France, before 1976, only metallic fuel was reprocessed on a commercial scale; oxide fuel reprocessing began in 1976 and is now by far the largest constituent of fuel reprocessed.

158. In previous UNSCEAR Reports occupational exposures at the commercial reprocessing facilities in

France and the United Kingdom were discussed. In addition, data were presented for a number of small-scale and/or prototype reprocessing plants. In this Annex consideration is largely directed towards the commercial-scale facilities, because it is these which determine the overall levels of both past and current exposures from this stage of the fuel cycle; data on prototype facilities are, however, provided for completeness.

159. External irradiation is the main contributor to occupational exposure in fuel reprocessing, although internal exposure may be significant in some operations, in particular those that involve actinides. Where internal exposures may be significant, personal monitoring is carried out, using methods appropriate to the circumstances of the exposure; these may include the wearing of personal air samplers, biological monitoring and whole body or lung counting. The contributions from internal exposure have in general, however, only recently been included in reported data on occupational exposure.

160. In previous UNSCEAR Reports a single estimate was reported for the normalized collective effective dose for reprocessing. The estimate was derived from the normalized collective doses estimated for each reprocessing facility and the respective amounts of fuel (in terms of energy equivalence) processed by them. In this Annex separate estimates are made of the normalized collective dose for the reprocessing of uranium metal and oxide fuels. There are several reasons for this. First, the fuels themselves have very different characteristics, as do the plants in which they are processed. Secondly, the normalized collective doses (normalized in terms of energy generation) for reprocessing the two types of fuel have differed by more than an order of magnitude in recent years. Any average value of normalized collective dose is, therefore, very sensitive to the respective amounts of fuel reprocessed and would probably not be valid for other periods or for projecting doses in the future. Thirdly, separate values are necessary in this analysis to provide normalized collective doses for each of the fuel cycles using different reactor, and consequently fuel, types.

161. Data on occupational exposures in reprocessing plants are summarized in Table 13, and some of the main features are illustrated in Figure XI. Few of the reported data contain estimates of the amount of fuel reprocessed or the energy generated from the fuel during its irradiation. In making estimates of world-wide levels of exposure from reprocessing and of average normalized collective doses, consideration has been limited to the commercial reprocessing of fuel at Cap de La Hague in France and Sellafield in the United Kingdom. Both metal and oxide fuels have been reprocessed at Cap de La Hague as well as small amounts of mixed oxide fuels; the relative amounts of each reprocessed in the three five-year periods are indicated in a footnote to Table 13. The doses reported for the reprocessing of Magnox fuels at Sellafield are probably overestimates. These doses are, with the exception of reactor operations, for the Sellafield site as a whole and will, therefore, include exposures from operations unconnected with Magnox reprocessing.

162. Worldwide levels of exposure from reprocessing metal fuels have been estimated by adding the data for the United Kingdom to that fraction of the total exposures occurring at Cap de La Hague attributable to the reprocessing of metal fuels. The normalized collective dose for each fuel type reprocessed at Cap de La Hague was estimated from the reported total collective dose arising in each five-year period and the amounts of each type of fuel reprocessed (the contribution of the small amount of mixed oxide fuel that was reprocessed was neglected). The normalized collective dose for metal fuel was estimated to be about 18 man Sv $(kt)^{-1}$ [6.7 man Sv $(GW\ a)^{-1}$] and for oxide fuel about 14 man Sv $(kt)^{-1}$ [0.7 man Sv $(GW\ a)^{-1}$]. The collective dose attributed to each type of fuel reprocessing in each five-year period was then derived as the product of the respective normalized collective dose and the amount of fuel processed. The numbers of workers attributed to the reprocessing of each fuel type were estimated from the collective doses, assuming that the average individual dose in each group was equal to that for the workforce as a whole.

163. The annual amount of metal fuel reprocessed worldwide, averaged over five-year periods, remained relatively uniform within a range of about 1,000-1,200 t (3-3.6 GW a). The number of monitored workers was typically 7,000-8,000. The average annual collective effective dose has decreased from about 50 man Sv in the first period to about 30 man Sv in the third. The normalized collective dose has declined similarly from about 50 to about 33 man Sv $(kt)^{-1}$ [17-11 man Sv $(GW\ a)^{-1}$], with a comparable decrease in the average annual effective dose to monitored workers from about 7 to about 4 mSv. The average fraction of monitored workers receiving annual doses in excess of 15 mSv decreased from about 0.16 to about 0.009 over the period analysed. These data are illustrated in Figure XI.

164. Over the period as a whole, about 80% of worldwide metal fuel reprocessing took place at Sellafield, with about 90% of the total collective dose arising there. The normalized collective doses for reprocessing metal fuel at Sellafield are typically greater than those at Cap de La Hague by a factor of about 2, apart from in the first five-year period, when the difference was greater. The respective average annual individual doses differ by a similar amount. A large fraction of the exposures at Sellafield has histori-

cally arisen during the decanning of fuel and in other operations conducted near the fuel storage ponds. This situation arose following significant contamination of the pond water from fuel corrosion in the early 1970s and is probably the main source of differences in exposures at Sellafield and at Cap de La Hague. Several factors have contributed to the reduction in exposures at Sellafield since the early 1970s, in particular the allocation of greater resources to ensure that doses were kept as low as reasonably achievable, measures taken to reduce the levels of contamination in pond cooling water and, more recently, the commissioning of a new facility for the receipt, storage and decanning of Magnox fuel.

165. The annual amount of oxide fuel reprocessed in France (and essentially worldwide), averaged over five-year periods, has increased from about 30 t in the first period to about 400 t in the last (about 0.5 to about 9 GW a). The number of monitored workers has increased over the same period from about 100 to about 4,000. The average annual collective effective dose has increased from about 0.4 man Sv in the first period to about 6 man Sv in the third. The normalized collective dose remained fairly uniform at about 14 man Sv $(kt)^{-1}$ [about 0.7 man Sv $(GW\ a)^{-1}$]. Another further reprocessing plant (UP3) was brought into operation at Cap de La Hague in 1990, and following this there was a significant decrease in the normalized collective effective dose, to about 5 man Sv kt^{-1} [0.19 man Sv $(GW\ a)^{-1}$]; on this evidence, somewhat lower normalized doses than reported in Table 13 can be expected in the future. The average fraction of monitored workers receiving annual doses in excess of 15 mSv decreased from about 0.06 to about 0.008 over the period analysed; the corresponding decrease in the fraction of the collective dose arising from individual doses in excess of that level was from about 0.3 to about 0.1.

166. With two exceptions, the doses reported in Table 13 include only exposures from external irradiation. Internal exposures are included in all of the data for Japan and for the United Kingdom from 1986 onwards. The reported doses in all other cases may, therefore, be underestimates, and caution should be exercised when comparing data that have been compiled in different ways. The contribution of internal exposure in the United Kingdom is estimated to be less than 10%.

2. Doses for specific tasks and occupational subgroups

167. The distribution of doses within the workforce involved in the reprocessing of nuclear fuel is, as in other occupations, not uniform, and doses somewhat higher than the average for the workforce as a whole will be received by groups of workers undertaking certain tasks. Statistics have been compiled for several groups of workers employed in the reprocessing of spent nuclear fuel and associated activities at the Sellafield reprocessing plant in the United Kingdom [S5]. The doses to these workers are illustrated in Figures XII and XIII. Annual doses from external irradiation are given in these Figures for the following six groups of workers for the period 1968-1988:

(a) fuel storage and decanning: process workers engaged in the storage under water of spent Magnox fuel and the subsequent removal of the magnesium alloy cladding before chemical dissolution of the fuel element;
(b) chemical separation: process workers engaged in the chemical dissolution of spent fuel to separate reusable uranium and plutonium from the fission product waste;
(c) maintenance: skilled and semi-skilled tradesmen engaged in the routine and breakdown maintenance of mechanical plant items;
(d) maintenance of new plant: skilled and semi-skilled tradesmen engaged in the installation of new mechanical plant items associated with operating facilities;
(e) plutonium finishing: process workers engaged in the conversion of the separated plutonium in the nitrate form into the final metal or dioxide product;
(f) waste processing: process workers engaged in the evaporation (i.e. concentration) and storage of the fission product waste stream separated from the actinides by the chemical reprocessing.

168. A generally downward trend in the average annual effective doses for each of the six groups has been maintained since the early 1970s, and substantial reductions have been achieved. The doses declined from several tens of millisievert in the early 1970s to levels in the range 4-10 mSv (Figure XII). For comparison, the annual effective dose, averaged over the whole workforce employed in reprocessing operations, fell from about 10 to about 3 mSv from 1975 to 1988. Several factors contributed to these reductions: the introduction of annual as opposed to age-related dose limits was influential, but the most important factor was the increased emphasis given, from the late 1970s onwards, by the regulatory authorities and the operator on keeping doses as low as reasonably achievable. ALARA became a central consideration in day-to-day plant operations and in the design of new facilities and the modification of the old plant. The introduction of a design standard for new facilities contributed further to the downward trends in dose, in particular through the 1980s, when a large number of new facilities were commissioned; this standard sought to ensure an average annual dose to the workforce of less than 5 mSv.

169. The reductions in collective effective dose (Figure XIII) are, in general, less pronounced. The trends in the collective dose are, however, generally downwards. Substantial reductions in the collective dose have been achieved in the two subgroups of reprocessing workers contributing most to exposures during reprocessing operations: workers associated with fuel storage and decanning and those associated with maintenance. In the former case the decrease reversed an increasing trend throughout the 1970s, which had resulted from the corrosion of fuel cladding and the contamination of storage ponds. Improvements in the condition of the storage pond and, more significantly, the commissioning of new fuel storage and decanning facilities were responsible for the reversal and for the sharp decline in the exposure of this occupational group. With one exception, the collective doses in the other subgroups exhibited a small decrease. The exception is the collective dose arising from the installation of new plant items; the increase here was associated with the almost twofold increase in the number of workers in this occupational category and doubtless also reflected an increased level of plant modifications and improvements.

F. RESEARCH AND DEVELOPMENT

170. In the UNSCEAR 1977 Report [U4], Annex E, it was estimated that the largest single contribution to the collective dose per unit energy generated came from research and development. A value of 14 man Sv $(GW\ a)^{-1}$ was estimated. This was subsequently judged to have been an overestimate, and in the UNSCEAR 1982 Report [U3], a value of 5 man Sv $(GW\ a)^{-1}$ was suggested as a more reasonable global average.

171. 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 under this category, and even when they are, uncertainties remain over 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 of the occupational exposures attributed in the preceding Sections to particular parts of the fuel cycle contain a contribution from research and development, but the magnitude of this fraction is difficult to estimate;

(c) normalization of collective doses from research have been made 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 equating the 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. Actually, the normalization should 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. Such considerations were at least partially responsible for the large downward revision in the normalized collective dose referred to in the preceding paragraph.

172. Occupational exposures arising in nuclear research, averaged over five-year periods, are summarized in Table 14. There is considerable variation in the levels of collective dose associated with research activities in each country, reflecting, among other matters, the relative role of nuclear energy in the national energy supply and the extent to which nuclear technology was developed domestically or imported from elsewhere. The reported annual collective effective doses range from a very small fraction of a man sievert (e.g. in Finland) to about 40 man Sv in the United Kingdom. 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 doses attributed to research in the United States and the United Kingdom are by far the largest of those reported (typically, annual doses range between 20 and 30 man Sv in the United States and 20 and 40 man Sv in the United Kingdom). The only other countries reporting annual doses of a few man sievert or greater are Canada, France, Germany and Japan, each of which has a significant nuclear research and development programme.

173. The data given for the United States need to be qualified because of the way in which they have been estimated. They have been extracted from data reported for all employees and contract workers of the Department of Energy [M3]; however, only a fraction of these exposures is associated with research related to the commercial nuclear fuel cycle (much is defence-related). In the absence of definitive data on the magnitude of this fraction, it has been approximately estimated from the total data of the Department of Energy by excluding those categories that are clearly

unrelated to commercial fuel cycle research. The data comprise the sum of exposures reported to arise in fusion, waste management and processing, plus one half of the exposures arising in the following categories: reactors, general research, offices, maintenance and support and other. The somewhat arbitrary inclusion of one half of the exposures attributed to these latter categories (which could not be excluded unequivocally), was intended to minimize the likelihood of underestimating the collective dose that should properly be attributed to commercial nuclear fuel cycle research. The doses given in Table 14 for the United States comprise about one third of the total doses reported by the Department of Energy but are still considered to be overestimates. In previous UNSCEAR evaluations, the total exposures reported by the Department of Energy were attributed to research associated with the nuclear fuel cycle; as a consequence, earlier worldwide predictions of exposures from this source may have been significantly overestimated.

174. Worldwide levels of occupational exposure associated with research are also given in Table 14. They were estimated from the reported data with extrapolation based on gross national product. 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 the basis for normalizing research were responsible for the change to gross national product. The regional groupings of countries were as specified in Section I.C, except that the former USSR was treated separately from the rest of Eastern Europe and, for the purposes of the extrapolation, grouped with those other regions for which no data had been reported or no data were available. The net effect of this change is that the doses for the former USSR were extrapolated on the basis of the normalized collective dose averaged over all reporting countries rather than over just those countries reporting data in Eastern Europe. The former was judged to be a more appropriate basis of extrapolation for a country with a large nuclear industry and research and development programme. The sum of gross national products for those countries reporting data was about 60% of the worldwide total. On average, therefore, the reported data have been scaled upwards by a factor of about 2; there is, however, considerable variation about this average for particular regions.

175. The annual number of monitored workers in research worldwide, averaged over five-year periods, remained fairly uniform, about 130,000. The average annual worldwide collective effective dose has decreased from 170 to 100 man Sv between the first and third five-year periods. The annual effective dose to monitored workers worldwide, averaged over five-year periods, fell from 1.4 mSv in the first period to about 0.8 mSv in the third. For those countries reporting data on this quantity, the fraction of the monitored workforce receiving annual doses in excess of 15 mSv decreased, falling from about 0.04 to about 0.01 over the period; the corresponding decrease in the fraction of the collective effective dose arising from annual doses in excess of that level was from about 0.4 to 0.3. These fractions were estimated from a set of data that was smaller than the set used to estimate doses, as not all countries reported data on these quantities; moreover, in some countries data on only one of the fractions were reported. Fewer data are available on the average doses to measurably exposed workers than on those to monitored workers; consequently no attempt has been made to estimate a worldwide average dose for this quantity. Those data that are available exhibit wide variations, with the average dose to measurably exposed workers varying from marginally in excess of that for the monitored workforce to many times greater.

176. It is of interest to compare the normalized collective doses (normalized in terms of gross national product, the unit for which is 10^{12} US dollars) for the different geographic or economic regions. For 1985-1989, the normalized collective dose averaged over all countries reporting data was about 5.8 man Sv per GNP unit (1989 prices). In comparison, the value for the OECD was about 5.7 man Sv per GNP unit; the values for Latin America, Eastern Europe (excluding the former USSR) and east and south-east Asia (non-centrally planned economies) were all within the range 0.8-1.4 man Sv per GNP unit. The value for India was considerably higher, about 20 man Sv per GNP unit. Considerable variation is, however, evident between countries within these broader regional groupings. For example, within the OECD, values were in the range 0.8-40 man Sv per GNP unit, the larger values being associated with those countries having large nuclear development programmes. The largest of these values was for the United Kingdom, where about half the total collective dose attributed to research arose from the operation and maintenance of a prototype steam-generating heavy water reactor (SGHWR); much of the remainder arose during the operation of reactors for material testing and radioisotope production and the operation of a prototype fast reactor and associated reprocessing and waste management facilities. Whether these exposures should be attributed to research is debatable, in particular those arising from operation of the SGHWR, where one of the considerations influencing its continued operation was the commercial revenue obtained from sales of electrical energy. This is another example of the difficulties encountered in trying to ensure comparability in the data reported for different countries.

177. Estimates have been made of the worldwide normalized collective dose expressed in terms of the nuclear energy generated during the same period as the research was undertaken. The deficiencies of this quantity were noted in paragraph 171, and it has been estimated mainly to provide a basis for comparison with estimates made on this basis in previous UNSCEAR Reports. The present analysis indicates that the global average of 5 man Sv (GW a)$^{-1}$ [U3], which was a major downward revision of the previous estimate, may still be a significant overestimate. It yields global average normalized collective doses of about 3, 1.5 and 0.6 man Sv (GW a)$^{-1}$ for the three five-year periods; even these values are considered to be overestimates. The sixfold decline in the normalized collective dose over the period analysed is largely an artefact of the normalization procedure, i.e. most of the reduction is a consequence of an increase in the rate of energy generation rather than of a decrease in the exposures associated with research.

178. An alternative, but perhaps more meaningful estimate of the normalized collective dose from research, albeit subject to several important simplifying assumptions, may be made by associating the total collective dose from research carried out in 1955-1989 with the energy generated during the same period plus that likely to be generated, largely with existing reactors, over the next 30 years, i.e. from 1990 to 2019. The total collective dose can be estimated from the worldwide data in Table 14, assuming that the worldwide average annual collective dose in five-year periods before 1975-1979 increased by 35 man Sv per period (i.e. the approximate increase per period between 1975-1979 and 1985-1989). The total energy generated may be estimated as the sum of the total nuclear energy generated up to 1989 plus that assumed to be generated over the next 30 years; the latter estimate assumed that the average rate of energy generation over this time would remain the same as that in 1985-1989. On this basis the normalized collective effective dose from research is estimated, in round terms, to be about 1 man Sv (GW a)$^{-1}$ and is considered to be applicable to research carried out in support of the commercial nuclear fuel cycle up to 1989. This value is judged to be a conservative estimate for a number of reasons, not least the probable overestimation of doses that should be associated with research in the period 1975-1989, the probable overestimation of doses attributable to research prior to 1975 and the probable underestimate of the energy generation that should be associated with the research already conducted. For the purpose of assessing overall values of normalized collective doses for the whole fuel cycle, this value of 1 man Sv (GW a)$^{-1}$ is assumed to be generally applicable for research, irrespective of when it was undertaken in the past, and to be independent of the fuel cycle considered.

G. CUMULATIVE DOSES

179. The estimation of cumulative occupational doses and their distributions in different workforces is a topic of some importance to those concerned with radiological protection. The cumulative dose received by a worker and its rate of accumulation provide a measure of the additional risk that may result from occupational radiation exposures. The absolute value of this risk and its distribution with time can be compared with risks in other occupations as an input to establishing occupational dose limits. There are, however, few published data on cumulative or lifetime doses, and it is therefore possible to provide only very indicative estimates of cumulative or lifetime doses for a limited number of occupations in particular countries. The increasing use of computerized databases for recording occupational exposures should result in more and better statistics on cumulative dose.

180. The most extensive analysis of cumulative or lifetime doses so far undertaken by the Committee was that for the UNSCEAR 1977 Report [U4]. Those dose estimates need to be revised to take account of subsequent developments in radiological protection standards and practice and of the simplifications that were used in the analysis. The more significant estimates of cumulative doses for nuclear fuel cycle facilities are summarized in this Section. Inevitably, differences exist in how the data on cumulative doses have been compiled and reported, and these limit the extent to which they can be directly compared.

181. *Summary of cumulative doses reported in previous UNSCEAR Reports.* Estimates of mean lifetime doses have been made in the United States for various groups of workers (employees of licensees of the Nuclear Regulatory Commission, the Department of Energy and the Navy) [E1]. Since these initial estimates were based on historical data on cumulative doses to workers whose employment had been terminated, no assumptions had to be made about the length of their working lifetimes. For most groups of workers analysed, the mean cumulative effective dose was estimated to be about 10 mSv. The estimates were not very sensitive to the year in which employment was terminated and showed only a small increase in the mean cumulative dose with increasing mean duration of employment (for mean periods in the range 1-10 years). The mean cumulative doses derived from such data may, however, be underestimates, because the data contain records for both permanently and temporarily terminated workers, and probably not all doses from previous periods of employment or with different employers will have been included. Estimates were also made of the maximum cumulative doses among the groups of workers analysed. Based on an analysis of trends in the data for workers in the

nuclear fuel cycle and for industrial radiographers, a maximum cumulative effective dose was estimated in both cases to be about 1.1 Sv; this was in accord with the maximum dose actually recorded in the data.

182. Sont et al. [S3] made estimates of lifetime doses for radiation workers in Canada based on data (up to 1983) contained in the National Dose Registry. The lifetime doses were estimated by linear extrapolation of each individual dose record for an assumed working lifetime of 40 years (i.e. the simplifying assumption adopted in the UNSCEAR 1977 Report). Lifetime doses predicted to be less than 10 mSv (equivalent, on average, to annual doses of 0.25 mSv) were excluded from the analysis. Estimates were made for each occupational category included in the registry.

183. Selected characteristics of the distributions of lifetime doses predicted for workers in the nuclear fuel cycle and industrial radiographers are given in Table 15. The mean lifetime effective dose for workers in the nuclear fuel cycle was predicted to be about 240 mSv, with the median being lower by a factor of about 2. Mean doses greater by a factor of 2 were predicted for particular occupations in the nuclear fuel cycle, i.e. chemical and radiation control, reactor operations and mechanical maintenance. The estimates need, however, to be qualified in the following respects:

(a) the assumption of 40 years for the period of exposure of all workers is very unlikely;
(b) because of the linear extrapolation of doses, no account is taken of how the dose profile may vary with the duration and starting date of employment;
(c) no account is taken of possible changes in dose limits or regulatory requirements over the period.

184. *Workers at uranium mines in the United States.* The distribution of cumulative doses received by uranium miners in the United States has been evaluated for the period 1967-1985 [B12]. The doses included only exposure by the inhalation of radon decay products and were derived assuming a conversion of 10 mSv WLM^{-1}; the values have been modified here using a conversion factor of 5.6 mSv WLM^{-1}. During this period, 50% of the miners had cumulative doses greater than 8.4 mSv. The percentage decreased steadily with dose, to 25% of the workforce greater than 28 mSv, 10% greater than 73 mSv, 1% greater than 240 mSv, and 0.1% greater than 380 mSv.

185. *Workers at reactors in the United States.* In its recent annual compilations of occupational exposures at commercial reactors and other facilities [R2], the Nuclear Regulatory Commission has explicitly addressed career or cumulative doses among reactor workers. The analysis was based on termination dose records, i.e. records of the cumulative dose at the time an individual terminated work at a reactor facility licensed by the Nuclear Regulatory Commission. It was limited to individuals who terminated their careers between 1977 and 1989 and to those working at reactors at the time of termination. The individual career or cumulative dose was estimated as the sum of all exposures received while working at reactors licensed by the Nuclear Regulatory Commission (but excluding doses that may have been received elsewhere). Data compiled in this way have a number of limitations that need to be recognized in order to be interpreted correctly. Two in particular are worthy of note: first, the data only include exposures that occurred at licensed reactors; and, secondly and perhaps more importantly, a large number of individuals may not have completed their careers on termination and may receive additional exposures during future work involving radiation. Since the mean age at which employment terminated was 36-38 years, there is considerable potential for further exposure at some future time. This consideration is, however, likely to be important only for employment that was terminated in more recent years. The likelihood of a return to radiation work would be expected to decrease with time since the employment terminated.

186. Data have been analysed for over half a million monitored workers, of whom about 300,000 had received a measurable dose (taken as any recorded dose during the period equal to or greater than 0.01 mSv), and statistics compiled on the variation of career or cumulative dose with length of employment, age and sex. Selected data from these statistics are summarized in Table 16 for those terminating employment between 1977 and 1989. For employment periods in the range of a few years to about 20 years, the average career dose increased fairly linearly with the duration of employment, with an average annual increment of about 3.5 mSv. For employment periods in the range of 20 to 25 years, the average annual increment was greater and typically about 5 to 6 mSv. This greater rate of dose accumulation, however, did not persist for even longer periods of employment. For employment periods greater than 25 years (average duration of about 40 years) the average career dose was about 70 mSv, that is an average annual increment of about 1.8 mSv. For career lengths in the range 20-25 years, about 3% of workers received career doses in excess of 500 mSv, with about 20% in excess of 200 mSv and about 40% in excess of 100 mSv. For those with career lengths of 10-15 years, the corresponding percentages were much reduced: about 0.1%, 3.6% and 14%, respectively. The corresponding percentages for other career durations can be found in Table 16.

187. The average career length for those terminating employment in 1977 was about 1 year, increasing to about 5 years in 1989. A less than proportional increase occurred in the average career dose over the same period; the increase was from about 10 mSv in 1977 to about 17 mSv in 1988 with evidence of a more substantial increase to about 26 mSv for those terminating employment in 1989. Data for subsequent years will be of interest to determine whether the latter is a statistical fluctuation or a reflection of an underlying trend. The average age at which employment was terminated changed slightly over this period, from 36 to 38 years.

188. Before the above-mentioned statistics were available from the Nuclear Regulatory Commission, Goldsmith et al. [G1] reported results from a more limited analysis of the cumulative doses for about 9,000 workers who at one time or another were employed at the Calvert Cliffs nuclear power plant in the United States. Two PWRs with a generating capacity of 825 MW each at Calvert Cliffs began operating commercially in 1975 and 1977, respectively. Workers were followed from their time of employment at the plant (including the period of construction) to the end of 1986. The mean follow-up period was 5.4 years, the mean duration of employment at the plant was 1.9 years and overall in the nuclear industry, 3.1 years.

189. For measurably exposed workers (about 80% of those monitored) the average career dose was 21 mSv; the average cumulative dose to contract workers, who comprised about one half of those measurably exposed, was 31 mSv and that to utility workers, 13 mSv. The cumulative collective effective dose to those workers was about 150 man Sv, of which only about one third (about 54 man Sv [B2]) was actually received at the Calvert Cliffs plant; the remainder was received at other licensed facilities. This mean cumulative effective dose of 21 mSv is somewhat greater than the overall average of about 14 mSv reported by the Nuclear Regulatory Commission for all reactor workers who terminated employment between 1977 and 1989. The cumulative dose for workers at the Calvert Cliffs nuclear power plant would be expected to continue to increase for those who had not yet terminated employment.

190. The data on cumulative doses were analysed in terms of the duration of employment at Calvert Cliffs, the duration of employment within the nuclear industry, the age at which employment began in the industry, the number of utilities at which an employee has worked, job category etc. [G1]. Selected characteristics of the distributions of cumulative dose for various employment durations are summarized in Table 17. The mean and median cumulative doses increase with increasing duration of employment in a broadly linear fashion. For contract workers, the average annual increment in dose was about 7 mSv and that for utility employees, about 3.5 mSv. The rate of accumulation of dose by utility workers was similar to that reported by the Nuclear Regulatory Commission for workers with career durations from 5 to 20 years; the rate of dose accumulation by contract workers was two times higher.

191. About 18% of contract workers and 6% of utility workers had received cumulative effective doses in excess of 50 mSv; the corresponding percentages for cumulative doses in excess of 100 mSv were 8.3% and 1.6%. The maximum cumulative dose reported was 470 mSv. The percentages of workers exceeding particular levels of cumulative dose after specified lengths of employment do not support any simple basis for extrapolation, but they nevertheless provide at least a rough indication of the levels of cumulative dose that may be experienced in the future, (or were already experienced in the past), by workers who were employed for longer periods in the industry.

192. The data also show a relationship between the cumulative dose and the number of utilities for which an employee has worked; this, perhaps, is not so surprising, since to at least some extent there must be a correlation between duration of employment and the number of utilities at which an employee has worked. The mean cumulative dose increases from about 8 mSv for contract workers who have been employed by only one utility to >100 mSv for those employed by 15 or more utilities. Cumulative doses were also estimated for selected job categories, and average values are summarized in Table 18. The higher doses received by contract workers compared with utility workers are apparent. By far the highest mean cumulative doses (in excess of twice the mean cumulative dose for the workforce as a whole) are received by workers in health physics.

193. In general, the cumulative doses and other related statistics reported for workers who, at one time or another, had been employed at the Calvert Cliffs reactor exceed those reported by the Nuclear Regulatory Commission for workers whose employment at reactors terminated in 1977-1989. These differences call into question the representativeness of career doses derived from termination records; one interpretation of the differences observed could be that career doses for workers terminating employment may be underestimates of those for workers having the same career duration but remaining in employment. Data in future years will help to elucidate this issue. The Calvert Cliffs data also highlight the significant differences in cumulative doses between utility and contract workers and between occupational categories. Further data on such differences would be useful.

194. *Workers at a Department of Energy facility in the United States.* An analysis is being undertaken of lifetime doses received at a large facility operated by the Department of Energy; research and development in support of both the commercial and defence nuclear fuel cycles are undertaken at such facilities. The analysis is still under way, but preliminary results have been presented in [M3]. The study includes more than 300,000 dose histories from more than 30,000 individuals who were employed at the particular facility at some time from 1944 to 1984. Only doses received at that facility are included in the analysis (i.e. doses received before or after to employment at the facility are not included). Data were collected on external and internal exposure, but the preliminary results are concerned solely with external exposure. These data show, for example, that no worker employed 20 years at the facility accumulated a dose greater than 500 mSv, and 10% of them accumulated a dose equal to or greater than 150 mSv. These data, while preliminary, show the magnitude of cumulative exposures over a 40-year period. When the analysis is complete, in particular when both internal and external exposures are included, it should provide further insight into the rate of accumulation of dose during working lifetimes.

195. *Workers at the Sellafield reprocessing plant in the United Kingdom.* An analysis [B9] has been made of the cumulative external radiation exposure, up to 1988, of male workers employed at the BNFL site at Sellafield, where various nuclear activities are undertaken in addition to the main one of fuel reprocessing. The trends in the cumulative dose as a function of follow-up time and as a function of the year in which the monitoring of a worker first took place are illustrated in Figure XIV; a subset of the data is given in Table 19. The data clearly indicate that the average cumulative dose in a group of workers followed for a given period decreases from earlier years to more recent years in which the group was first monitored; the effect becomes more pronounced for longer follow-up periods. For a 20-year follow-up period, the average cumulative dose for those who were first monitored in 1950 is about 400 mSv; this is greater by a factor of almost 2 than the average cumulative dose received by those first monitored in the mid- to late 1960s. For a 38-year follow-up period (the maximum), the average cumulative dose for those first monitored in 1950 is about 750 mSv; the cumulative doses for the same follow-up period for those first monitored in 1960 can, at this stage, only be speculative, but by extrapolating existing data and taking into account the effect of a reduction in dose limits, the average cumulative dose for this group of workers appears unlikely to exceed 350 mSv. The decreasing rate of increase in the average cumulative dose with length of follow-up period (for a given year of first monitoring) illustrates the considerable potential for overestimating cumulative doses, if derived on the basis of linear extrapolation of past experience.

196. Further useful insights could be obtained from these data if they could be reported in various disaggregated forms, for example, the distribution of cumulative doses (in addition to the mean) for particular choices of the year of first monitoring and follow-up period, age at first monitoring and main type of work undertaken etc.

197. *Workers at nuclear establishments in the United Kingdom.* As part of an analysis of the National Registry for Radiation Workers in the United Kingdom [K5], data were reported on the cumulative doses from external irradiation of workers. These external doses are summarized in Table 20 in three different formats: for each of the major employers of radiation workers included in the study, for year of birth of the workers and for the year in which radiation work began. Since the data include cumulative doses for both current and past employees in each of the organizations up to about 1988, they comprise individual doses accumulated over a wide range of different working periods and at different times.

198. While the data are of general interest, they are particular to the composition of the past and current workforce and their employment characteristics; they cannot (at least in the form in which they have been reported) be used to estimate cumulative doses for different durations of employment for either the past or current workforce. To enable such estimates to be made, the data would need to be disaggregated, at least into the form in which the data for workers at BNFL Sellafield are presented in Table 19. Equally, it would be inappropriate, indeed potentially misleading, to attempt, in the absence of additional information, to draw any firm conclusions about the levels of cumulative dose in different industries based on direct comparisons between the data in Table 20. The respective data may comprise workforces having very different sizes, age structures and employment durations, and these characteristics may, moreover, have varied considerably over time. For example, a major change in the size of a workforce in the recent past could considerably distort the estimated cumulative dose relative to that for an industry having a relatively uniform or even declining workforce.

199. Notwithstanding these qualifications, the data exhibit a number of interesting features. The average cumulative dose at sites of BNFL was greater by a factor of more than 2 than that at research establishments of the Atomic Energy Authority and at

reactors operated by Nuclear Electric. This is to be expected given the somewhat higher doses experienced during reprocessing and at the older reactors operated by BNFL. Smaller average cumulative doses occurred at Ministry of Defence establishments, in particular at the Atomic Weapons Establishment; this reflects the much smaller levels of external dose experienced in the processing of materials for nuclear weapons. The cumulative doses to those monitored by the Defence Radiation Protection Service (activities largely connected with the nuclear submarine programme) are for both civilian and naval personnel; one contributory factor to the lower levels in this group is the relatively short periods, compared with a working lifetime, that naval personnel spend in this role.

200. Cumulative dose as a function of the year of birth of the worker generally decreased, as would be expected, with time; this trend reversed for the earliest years analysed because these workers, on average, had spent a smaller part of their working lives in radiation-related work. Disaggregation of the data according to duration of employment in radiation work would yield statistics of somewhat greater interest and value. The cumulative dose as a function of the year radiation work started shows, apart from the early years, an expected decrease with time. Two factors contribute to this decrease: first, the greater period of time, on average, spent on radiation-related work and, secondly, the generally downward trend in annual doses. The rate of decrease in the average cumulative dose between the periods for which the data are reported is not uniform, indicating that there are factors operating that cannot be discerned from the data in its aggregated form. Again, disaggregation of these data in terms of year and age at which work with radiation began, follow-up period, type of work undertaken etc. is needed for the full potential of these data to be realized.

201. *Summary.* In the past few years significantly more data have been reported on cumulative doses during working lifetimes. This was to have been expected from the increasing development and use of computerized databases for occupational exposures. While such data are sparse in comparison with data on annual doses, the imbalance is likely to be reduced in the future. To facilitate the comparison and/or aggregation of cumulative doses for different occupational categories and countries, much more attention should be given to the development and use of common approaches for the compilation and reporting of these data. If data could be presented in sufficient detail to allow their analysis as a function of the year and age of starting radiation-related work, employment duration and type of work undertaken, much greater uniformity in reported cumulative doses and their comparison could be achieved.

H. SUMMARY

202. Worldwide occupational exposures from each stage of the commercial nuclear fuel cycle are summarized in Table 21 and illustrated in Figure XV. The data are annual values averaged over five-year periods. The number of workers in the commercial nuclear fuel cycle rose from an average of about 560,000 in the first five-year period to about 880,000 in the third. About a quarter of a million of these workers were involved in uranium mining and about 130,000 in research and development; the remainder were largely employed in reactor operations (about 150,000 on average in the first five-year period increasing to about 430,000 in the third period). The annual collective effective dose, averaged over five-year periods, increased from about 2,300 man Sv in the first period to about 3,000 man Sv in the second but decreasing in the third period to about 2,500 man Sv. By far the largest contributors to the total collective dose were uranium mining and reactor operation (about 50% and 35%, respectively, averaged over the period 1975-1989).

203. The average annual effective dose to monitored workers in the whole fuel cycle decreased progressively, from an average of 4.1 mSv in the period 1975-1979 to an average of 2.9 mSv in the period 1985-1989. There is, however, considerable variation about these average values for different stages of the fuel cycle (see Figure XV). Downward trends in dose with time are evident for all stages of the fuel cycle; the magnitude of the decrease varies, however, with the stage of the fuel cycle, and there were also considerable year to year variations that are not apparent in the five-year averages. The dose distribution ratios are illustrated in Figure XVI. The fraction, averaged over five-year periods, of monitored workers receiving annual doses in excess of 15 mSv has decreased from about 0.20 to about 0.10 between the first and third periods; the corresponding decrease in the fraction of the collective effective dose has been from about 0.63 to about 0.42. Workers in mining and reactor operation are the main contributors to these two fractions.

204. The normalized collective effective doses for each stage of the fuel cycle are shown in Figure XVI. The collective dose from mining, milling, fuel fabrication and fuel reprocessing have been normalized to the energy equivalent of uranium mined or milled or the fuel fabricated or reprocessed in the respective periods. The estimate of 1 man Sv $(GW\ a)^{-1}$ for research associated with the fuel cycle has been assumed in each period. The overall normalized collective effective dose (i.e. averaging over all stages in all fuel cycles, taking account of their relative magnitudes) is estimated to be 18, 17 and 12 man Sv $(GW\ a)^{-1}$ in 1975-1979, 1980-1984 and 1985-1989,

respectively. These normalized doses exclude fuel reprocessing, which would add about 0.7 man Sv (GW a)$^{-1}$ for oxide reprocessing, and 10-15 man Sv (GW a)$^{-1}$ for Magnox fuel reprocessing, with the larger value appropriate for earlier times.

205. The components of normalized collective effective doses for the separate fuel cycles based on the various reactor types are summarized in Table 22; the results are illustrated in Figure XVII. For ease of comparison and completeness, a contribution from reprocessing is indicated in each case, whether or not reprocessing of that fuel type has occurred or indeed is even foreseen. With the exception of the fuel cycles based on GCRs, reactor operation makes the largest contribution to the normalized collective effective dose, with the only other large contribution coming from mining. For fuel cycles based on other than GCRs, the normalized collective dose varied within a range of 17-27 man Sv (GW a)$^{-1}$ in the first five-year period and 10-14 man Sv (GW a)$^{-1}$ in the third period; the decrease was mainly due to decreases in the doses arising during reactor operation.

206. The normalized collective doses for the fuel cycle based on AGRs remained relatively uniform over the whole period, about 9 man Sv (GW a)$^{-1}$. This is significantly less than for fuel cycles of other reactor types because of the lower collective doses for the reactors. Uranium mining is the largest contributor to the normalized collective dose for this fuel cycle accounting for 60% or more. For the fuel cycle based on the Magnox reactor, the normalized collective effective dose declined from 36 man Sv (GW a)$^{-1}$ in the first period to 27 man Sv (GW a)$^{-1}$ in the third. The reprocessing of Magnox fuel makes by far the greatest contribution to the total normalized dose (40%-50%). Reactor operation and mining are the only other significant contributors, with similar contributions. Two factors have been largely responsible for the greater normalized doses associated with the fuel cycle based on Magnox reactors. First, because of its much lower irradiation, the generation of unit electrical energy with Magnox fuel requires larger amounts of uranium to be mined, fuel to be fabricated and fuel to be reprocessed than with fuel cycles based on other reactor types; secondly, the doses from Magnox reprocessing have been greater than anticipated because of major contamination of pond cooling water from fuel corrosion that occurred in the first half of the 1970s at the Sellafield plant in the United Kingdom.

207. Insufficient data are available on cumulative or lifetime doses to enable reliable estimates of worldwide levels or of trends in their values; this situation, however, is changing through the increasing use of computerized databases for occupational exposures and the compilation of data for epidemiological studies on workers. Much improved estimates of cumulative doses can, therefore, be expected over the next few years. To facilitate the comparison and/or aggregation of cumulative doses for different occupational groups and/or countries, it would be useful if data could be reported in a manner which enabled them to be evaluated in terms of the following quantities: the year and age of starting radiation-related work, employment duration and type of work undertaken.

III. DEFENCE ACTIVITIES

208. 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). The levels of exposure in the first two of these categories are assessed separately and then the overall levels of exposure from defence activities are assessed. It must be recognized that there will be some lack of rigour and/or uniformity in the attribution of exposures to particular defence activities and in the separation of exposures between defence activities and the commercial nuclear fuel cycle. This is inevitable, given differences in how data have been categorized and reported in different countries. In this Annex, for example, all exposures occurring in the mining, milling and enrichment of uranium have been attributed to the commercial nuclear fuel cycle; at least a fraction of these exposures should, however, have been attributed to defence activities. Similarly, some of the exposures attributed to reprocessing and to research and development in the commercial nuclear fuel cycle should also be attributed to defence activities. For these reasons, the doses reported in the remainder of this section are likely to be underestimates of those that should properly be associated with defence activities. The data are not complete for radiation-related defence activities in all countries.

A. NUCLEAR WEAPONS

209. Nuclear weapons have been developed, tested and deployed in the military services of 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; the intake of these materials into the body by inhalation or ingestion (or absorption through the skin in the case of tritium) and 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.

1. Annual doses

210. Data on occupational exposures from the nuclear weapons programmes in the United Kingdom and the United States are summarized in Table 23 and are illustrated in Figure XVIII. The reported doses are for external irradiation only and include exposures arising in the development and production of weapons as well as in their subsequent handling, although the latter makes only a modest contribution to the overall levels of exposure. The total number of monitored workers (i.e. summed over both countries), averaged over five-year periods, remained relatively uniform over the period analysed, at about 21,000. The total annual collective effective dose, averaged over five-year periods, also varied little and was typically about 14 man Sv. This average value, however, disguises somewhat greater year-to-year variations within the range 10-20 man Sv, although there were no significant trends in the values. About 80% of both the total number of monitored workers and the collective dose were in the United States.

211. The annual effective dose to monitored workers, averaged over all workers and over five-year periods, was about 0.7 mSv in all three periods. Average individual doses in the United States were broadly comparable with those for the total workforce; somewhat higher average annual doses, about 1 mSv, were experienced in the United Kingdom up to the middle of the 1980s, but these later decreased by a factor of more than 2. The annual doses to measurably exposed workers (United States data only) were typically greater than those to monitored workers by a factor of about 2. All the individual and collective doses referred to here need, however, to be qualified. They are the doses recorded by the dosimeter. The actual effective doses would be smaller by a factor of at least 2. This discrepancy is due to the relatively low energy of the gamma-radiation emitted by weapons materials. Data (available only for the United Kingdom) on the fraction of workers receiving annual doses in excess of 15 mSv indicate that, in general, this fraction is zero or very small.

212. Fewer data are available on internal exposures. In the United Kingdom, records of internal exposures from the intake of actinides into the body (and, to a lesser extent, tritium) have been kept since 1986. Doses from intakes of actinides have been measured using personal air samplers worn by individual workers, and those from intakes of tritium have been measured by urine monitoring. Each year, about 1,000 workers were monitored for uranium and plutonium. The average committed effective dose from intakes in 1986 was about 0.15 mSv from uranium and plutonium, and by 1989, these doses had decreased to about 0.05 mSv. In each year also about 500 workers were monitored for tritium intake, and the average annual dose declined from about 0.17 mSv to 0.1 mSv between 1986 and 1989. The resulting collective dose from internal exposure is, therefore, small in comparison with that from external irradiation. Indeed, any underestimate as a result of its omission from the doses reported in Table 23 (at least for the United Kingdom data) is negligible in comparison with the overestimate of external dose as a result of including the dosimeter measurement directly into dose records.

213. Comparable data are not available for other countries that have developed nuclear weapons. More limited data [B10, N2] have, however, recently become available on exposures in reactors and chemical reprocessing plants used in the production of weapons-grade materials in the former USSR. Only individual doses are reported, and in the absence of information on the size of the workforce, no estimate

could be made of collective doses. Moreover, data on exposures arising at other stages of weapons production and testing would be needed before these data could be properly compared with the data presented in Table 23. Nonetheless the data provide some perspective on the levels of dose encountered in the weapons programme in the former USSR.

214. The variation in average individual dose (external irradiation only) to workers in reactors and chemical reprocessing plants is illustrated in Figure XIX. In the late 1940s these average doses were substantial (about 1 Sv) in both the reactors and chemical plants. They had declined to about 100 mSv by the late 1950s and to about 10 mSv by the late 1960s. Thereafter the rate of decrease in dose was more modest. The distributions of dose among the respective workforces are also illustrated in Figure XIX. In the late 1940s and early 1950s, annual doses in excess of 1 Sv were received by a few tens of per cent of workers in both the reactors and chemical plants, with 1%-2% receiving annual doses in excess of 4 Sv. In the chemical plants, essentially the whole workforce was exposed to annual doses in excess of 25 mSv before the early 1960s; the percentage of workers exceeding this level of exposure declined rapidly through the 1960s to essentially zero by the end of that decade. In the reactors, the percentage of workers receiving annual doses in excess of 25 mSv decreased during the 1950s, from essentially 100% to a few tens of per cent; this share subsequently varied from a few to a few tens of per cent through the 1960s before decreasing to a low level in the 1970s.

2. Cumulative doses

215. The distribution of cumulative doses among workers employed in the nuclear weapons programme in the United Kingdom at the end of 1989 [D1] is summarized in Table 24. Less than 1% of the workforce in 1989 received cumulative effective doses in excess of 100 mSv and none received in excess of 500 mSv. In practice all the percentages are overestimates because the effective dose and the dosimeter measurement are assumed to be equivalent.

B. NUCLEAR-POWERED SHIPS AND THEIR SUPPORT FACILITIES

1. Annual doses

216. Nuclear-powered ships (submarines and surface vessels) are operated by several navies, in particular China, France, India, the former USSR, the United Kingdom and the United States. Pressurized water-cooled reactors are used as 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. Data are not available from all countries, but compilations have been made of the exposures arising in the United Kingdom [D1, M11] and the United States [M1, M9, M10, N1, S2].

217. Data on occupational exposures from nuclear-powered ships in the United Kingdom and the United States are summarized in Table 23. The total number of ships in the two navies increased from an average of 135 in 1975-1979 to an average of 167 in 1985-1989. Averaged over the whole period, about 90% of these belonged to the United States navy. The total number of monitored workers increased from about 42,000 in 1975-1979 to about 63,000 in 1985-1989. Most of this increase occurred in the United States, as the number of workers in the United Kingdom remained relatively constant, at about 6,000, throughout the period.

218. The total annual collective dose decreased from about 92 man Sv in the first five-year period to about 57 man Sv in the third. Averaged over the whole period, the contribution of the United States to the total collective dose was about 73%; the magnitude of the contribution differed, however, between five-year periods. The annual dose averaged over all monitored workers decreased from about 2.2 mSv in the first five-year period to about 0.9 mSv in the third; the corresponding decreases in the two countries were from about 4.1 to about 1.9 mSv in the United Kingdom and from about 1.9 to about 0.8 mSv in the United States. Over this same period the fraction of all monitored workers receiving annual effective doses in excess of 15 mSv decreased from about 0.5 to about 0.1; in the United Kingdom the values of this quantity were, in general, about 50% larger than the average values.

219. Estimates have been made of the normalized collective effective dose, with the normalization performed in terms of the number of ships. Averaged over both countries, the annual normalized collective dose has decreased by a factor of about 2, from about 0.7 man Sv per ship in 1975-1979 to about 0.34 man Sv per ship in 1985-1989. The corresponding decrease in the annual normalized dose was from about 1.8 to about 0.6 man Sv per ship in the United Kingdom and from about 0.6 to about 0.3 man Sv per ship in the United States. These and previously identified decreases in exposures were achieved despite a significant increase in the number of ships in service and undergoing refit and maintenance during the period.

220. In general, higher exposures were received by shore-based workers, in particular those who were involved in inspection, maintenance (including refitting and refuelling operations) and repair inside the reactor compartment or on components that form the primary cooling circuit. By comparison the exposures of on-board personnel were generally much lower, owing to the shielding provided around the reactor and its associated systems. These differences are illustrated in Figure XVIII.

221. Averaged over the whole period and both countries, about 45% of the total workforce comprised shore-based workers, although there were significant variations about this average value both with time and between countries; for example, in the United Kingdom about 80% of all workers were shore-based. About 70% of the total collective dose over the whole period was received by shore-based workers, again with variation about this average value between countries and with time (e.g. about 85% of the exposure in the United Kingdom was received by shore-based workers).

222. The most noticeable difference between the two groups of workers is in their average annual doses. Averaged over both countries and over five-year periods, the average annual dose to shore-based workers has decreased from about 3.2 mSv to about 1.5 mSv between the first and third periods; the average doses to on-board workers were typically two to three times lower, decreasing from about 1.3 to about 0.5 mSv over the same period. The data for the two countries exhibit the same trends, but the absolute and relative magnitudes of the doses differ, sometimes significantly. Somewhat higher than average doses may be received by particular subgroups within the broader occupational groupings. For example, at civilian dockyards in the United Kingdom, where much of the maintenance and refitting of ships is undertaken, average annual doses were as high as 10 mSv in some years, although they decreased, in general, over the years. Differences are also apparent between the two groups in terms of the fraction of workers receiving annual doses in excess of particular levels (15 mSv for the United Kingdom data and 10 mSv for the United States data), with the fraction being considerably greater for shore-based workers. In the UK the distribution ratio, NR_{15}, for shore-based workers decreased from about 0.09 to about 0.02 between the first and third five-year periods; the corresponding fractions of on-board workers exceeding that dose decreased from about 0.03 to about 0.01 over the same period. In the United States the distribution ratio, NR_{10}, for shore-based workers decreased from about 0.1 to about 0.03 between the first and third five-year periods, while the ratio for on-board workers decreased from about 0.02 to about 0.001.

2. Cumulative doses

223. The distributions of cumulative doses among workers employed in the naval nuclear propulsion programme in the United Kingdom at the end of 1989 and in the United States at the end of 1991 are summarized in Table 24. Data are given separately for on-board and shore-based personnel and for the total workforce in the case of the United Kingdom. Somewhat higher cumulative doses are evident for shore-based personnel than for those on board, because the latter are naval personnel, whose mean time of service in this capacity is much shorter than that of the mainly civilian workforce in the shore-based facilities, where much of the occupational exposure occurs. In general, the percentages of workers exceeding particular levels of dose in the United Kingdom surpass those in the United States, although not by a great amount.

224. In the United Kingdom, the highest cumulative dose recorded among shore-based personnel was about 800 mSv accrued over a 30-year period. The distribution of cumulative doses varies considerably from one shore-based facility to another, with much higher doses at civilian dockyards, where much of the maintenance etc. is undertaken. Cumulative doses at operational naval bases are lower, both because of differences in the nature of the work carried out and the generally greater mobility of naval personnel. For example, about 20% of the civilian dockyard workforce received a cumulative dose in excess of 100 mSv compared with about 8% for all shore-based personnel.

C. ALL DEFENCE ACTIVITIES

1. Annual doses

225. Data on occupational exposures from all defence activities are summarized in Table 23 for the United Kingdom and the United States and for the sum of both sets of data; the data are illustrated in Figure XVIII. The data include exposures from weapons production and testing, from nuclear ships and from a wide range of other uses of radiation that can be attributed to defence-related activities. These uses include all those encountered in civilian occupations, for example non-destructive testing, transport, research, education and medicine. The contribution from these other sources to the overall levels of exposure from defence-related activities in the United Kingdom varied from about 20% in the late 1970s to only a few per cent in the later 1980s. In the United States this contribution, averaged over the whole period, was about 15%, decreasing over time. By far the greater part of both the total defence

workforce and the total collective dose are associated with nuclear ships; this is not surprising, given the large number of nuclear ships operated by these two countries.

226. The total number of monitored workers, averaged over five-year periods, has increased from about 100,000 to about 130,000 between the first and third periods. This increase largely occurred in the United States; the number of monitored workers in the United Kingdom remained relatively constant, about 12,000, over the period analysed. The total annual collective dose, averaged over five-year periods, decreased from about 140 to about 84 man Sv between the first and third periods; averaged over the whole period, about 75% of the total collective dose was received by workers in the United States. The annual dose to monitored workers, averaged over both countries and over five-year periods, has decreased from about 1.3 mSv to about 0.7 mSv between the first and third periods. Given the much larger contribution made by the United States to the overall data, these average individual doses mainly reflect experience in that country; over the same period, the average annual doses to workers in the United Kingdom were somewhat larger, decreasing from about 3 mSv to about 1.2 mSv.

227. The above data need qualifying with regard to their completeness, in particular 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 the 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).

2. Worldwide annual doses

228. The data presented above for all defence activities include occupational exposures for only two countries, the United Kingdom and the United States. Occupational exposures from defence-related activities in China, France and the former Soviet Union (i.e. the other countries which have developed nuclear weapons and/or that operate nuclear navies) are not available. Any estimate of worldwide occupational exposures from defence activities can, therefore, be made only by extrapolating the available data to these other countries. Inevitably, this can only be done very approximately, and neither of the methods of extrapolation presented in Section I.C is appropriate.

229. It would be most useful if the extrapolation could be 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 programmes. Data sufficient for making these extrapolations could probably be compiled on weapons stockpiles worldwide and their potential yields and on the worldwide capacity of nuclear navies. The validity of such extrapolations would depend, however, on the representativeness of normalized collective doses derived from experience in the United Kingdom and the United States. The limited data for the nuclear weapons programme in the former USSR (see Figure XIX) do not augur well in this respect; in particular, the reported doses in earlier years in that country were far in excess of those experienced elsewhere. These much higher doses largely preclude the use of normalized collective doses derived in one or two countries for estimating worldwide exposures from defence activities.

230. Pending the acquisition of further data, a very simple approach has been adopted 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 underlie 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 large in comparison with either those in the former Soviet Union or in the United States. 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. Given the coarseness of the underlying assumptions, it would 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 300-400 man Sv. This estimate is inevitably associated with much uncertainty, which can only be reduced by relevant data from China, France and the former Soviet Union.

3. Cumulative doses

231. The cumulative doses to personnel employed in defence activities in 1989 in the United Kingdom are summarized in Table 24, where data are given separately for service and civilian personnel. Estimates of cumulative doses to defence workers in the United Kingdom [D1] have also been made by the NRPB from data held within the Central Index of Dose Information and the National Registry of Radiation Workers, and these are summarized in Table 25. Direct comparisons should not, however, be made between these two sets of data, as the composition of the respective workforces and the time over which data were compiled differ; these differences are summarized in footnotes to Table 25. Data identified under the heading "weapons programme" in Table 25 are specifically for workers at the Atomic Weapons Establishment but can, to a good approximation, be assumed to be representative of exposures associated with the weapons programme as a whole. The data under the heading "other defence activities" are for all defence workers apart from those at the Atomic Weapons Establishment; most of these exposures will, however, be associated with the naval nuclear propulsion programme.

232. The mean cumulative dose to classified radiation workers in all defence activities in the United Kingdom is 29 mSv; for the weapons programme the mean dose is 21 mSv, and for the naval nuclear propulsion programme it is 37 mSv. These averages, however, disguise significant differences between employees of the Ministry of Defence and contract workers. In the naval nuclear programme the cumulative dose to contract workers is greater by a factor of more than 3 than that to employees (58 mSv compared with 18 mSv), whereas in the weapons programme the dose to contract workers is less than half that to employees (9.4 mSv compared with 21.8 mSv). About 7% of all workers received cumulative doses in excess of 100 mSv and about 0.2% received in excess of 400 mSv; for contract workers in the naval nuclear programme, the corresponding values were about 19% and 0.7%.

233. The mean cumulative doses to workers in the National Registry of Radiation Workers are lower (typically by a factor of about 2) than those in the Central Index of Dose Information, because contractor employees are not included but both classified and non-classified employees are. These results are of interest mainly because they provide an opportunity to determine what fraction of the cumulative dose arises over particular periods or age intervals. Data are given for doses accumulated to age 30 years, and the mean cumulative dose over this period is about one third of the mean cumulative dose overall.

IV. INDUSTRIAL USES OF RADIATION

234. Radiation is used for many purposes in industry. Most of these uses involve sealed radioactive sources or equipment that is electronically energized to produce radiation, for example x-ray machines, electron microscopes and particle accelerators. Some of the main industrial uses include industrial radiography, well logging, luminizing, non-destructive testing, thickness gauging, tracer techniques and the use of x rays for a variety of purposes, like crystallographic and fluoroscopic analyses of materials. The levels and trends in occupational exposure from industrial uses of radiation are reviewed in this Chapter together with those arising during the production of radioisotopes for medical and industrial purposes. In addition, exposures from the use of radiation in research (excluding research undertaken in support of the nuclear power industry) are estimated to the extent that they can be separately identified.

235. The compilation of reliable statistics on occupational exposure in industry is complicated by the diversity of uses to which radiation is put and differences in the way data are reported by different countries, in particular the number and nature of the occupations for which data are reported separately. By far the greater number of occupational exposures in general industry are small, and this has doubtless influenced the relative lack of detail, or disaggregation, in their reporting. In general, data have been reported separately only for those few occupations with the potential for higher doses. Since the availability of reported data clearly determines the level of detail that can be included in this review, consideration is limited to the levels of exposure in industry overall and in those few groups where higher doses could arise and/or for which a number of countries have reported data separately. These separate groups comprise industrial radiographers, luminizers, radioisotope producers and well loggers.

236. Differences may exist in the procedures used in various countries to group workers occupationally, and this places limitations on 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 respective 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 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.

237. National data on occupational exposures arising from the industrial use of radiation are given in Table 26 for workers in each of the following areas: industrial radiography, luminizing, production and distribution of isotopes, well logging, tertiary education and research institutes, accelerators and all industrial uses of radiation grouped together. Worldwide levels of exposure have been estimated from the reported national data for each industrial use, with extrapolation within particular regions based on gross national product. In general, the collective dose was well correlated with gross national product, but there were exceptions to this for some countries. The degree of extrapolation needed varied with the industrial use considered but typically was about a factor of 2 on average; there was, however, considerable variation about this average value for particular regions or periods. For some industrial uses insufficient data were available to allow reliable extrapolation.

A. INDUSTRIAL RADIOGRAPHY

238. Industrial radiography is carried out in two quite different sets of conditions. First, it may be undertaken at a single location, usually in a permanent facility that has been designed and shielded for this purpose; in this case items to be radiographed are brought to the facility. Secondly, it may be undertaken at multiple locations in the field, in which case the radiographic equipment is transported to the place of interest. The ease and efficacy of exercising control, supervision and protection in the two cases may be different, and this may have implications for the resulting occupational exposures. Few of the reported data, however, distinguish between exposures from the two types of radiographic practice.

239. Worldwide levels of dose have been estimated from national data by extrapolation within regions based on gross national product. The sum of the gross national products for those countries reporting data was about 35% of the worldwide total in the first five-year period, increasing to about 65% in the third. On average, therefore, the reported data have been scaled upwards by a factor of about 2 with considerable variation, however, about this average for particular periods and regions. Estimates of the numbers of workers and doses in industrial radiography worldwide are illustrated in Figure XX. The annual number of monitored workers in industrial radiography, averaged over five-year periods, is estimated to have increased from about 70,000 in the first period to about 110,000 in each of the last two periods. 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 significantly to about 160 man Sv in the third. Roughly half of these collective doses are estimated to have occurred in countries comprising the OECD and about one quarter to one third in the countries of Eastern Europe.

240. The annual effective dose to monitored workers, averaged over five-year periods, fell progressively from about 2.6 mSv in the first period to about 1.4 mSv in the third. This same downward trend is evident in the data for most countries and regional groupings, but there is considerable variation between countries in both the level of the dose and extent of the decrease. For example, average doses to monitored workers were as low as 0.2 mSv in some countries (e.g. France and the German Democratic Republic) to as high as 13 mSv in others (the former USSR). From data reported, the fraction of the monitored workforce receiving annual doses in excess of 15 mSv is estimated to have decreased from about 0.04 in the first period to about 0.03 in both the following periods; the fraction of the collective effective dose arising from annual doses in excess of the same level is estimated to have changed little over the period, remaining at about 0.4. These fractions were estimated from a smaller set of data than used to estimate collective and individual doses and, as a consequence, are less reliable indicators of worldwide levels.

241. Relatively few data are available on average doses to measurably exposed workers as opposed to monitored workers, and no attempt has been made to estimate a worldwide average dose for the former quantity. There is considerable variation between countries in both the absolute levels of these doses and in the ratio of these to the average dose to monitored workers. This ratio varies from about 1 to more than 10. While differences in operational practice and standards of protection will account for some of this variation, the more likely causes are differences in how doses are measured and formally recorded, in who in the workforce is to be monitored and the

completeness of the occupations or uses included in the data reported.

242. Data on occupational exposures arising from fixed and mobile radiography are included in Table 26 under "industrial radiography" for those few countries where exposures in the respective practices could be separated. Data are given for the Netherlands, the United Kingdom and the United States; the totals (or averages) of the reported data are dominated by exposures in the United States, because the number of workers and the collective dose are generally much larger than in other countries for which data are available.

243. The annual doses, averaged over five-year periods and over all reported data, for workers undertaking mobile radiography, (where control and supervision are potentially more difficult), exceed those arising in fixed radiography. The average annual dose from mobile radiography remained relatively unchanged over the period, about 3 mSv, whereas that from fixed radiography declined almost fourfold, from about 1.4 to about 0.4 mSv. The values of the ratios SR_{15} and NR_{15} are, likewise, larger for those involved with mobile than with fixed radiography, with the difference being more pronounced in the case of SR_{15}. Exposures in the Netherlands are much lower than average, but they do exhibit the same general trends with respect to the differences between mobile and fixed radiography. In the data for the United Kingdom, however, only small differences are evident in the occupational exposures for the two types of radiography.

244. A further statistic of interest in the present context is the number of workers receiving accidental overexposures. There were indications in the past that radiography workers, because of the nature of their work (particularly in the case of mobile radiography), might be more liable to receive overexposures than workers in most other occupations. Data on the percentage of radiographers receiving doses in excess of an annual effective dose of 50 mSv, together with the percentage of the collective dose arising from individual doses above the same level, are summarized in Table 27. The data are not complete enough to enable any time trends to be determined. Averaged over the whole period and over all countries, the data indicate that about 0.1% of industrial radiographers receive exposures in excess of 50 mSv each year; about 6% of the average annual collective dose from radiography is estimated to result from such exposures. Significant variation is apparent about the weighted average values for particular countries.

245. If these percentages are assumed to be representative globally, about 100 radiographers worldwide receive doses in excess of 50 mSv every year. While in absolute terms this number is not large, the occurrence of overexposures (normalized to the size of the workforce) in industrial radiography exceeds that in most other occupations. By comparison, in 250,000 monitored workers of the United States Nuclear Regulatory Commission licensees not involved in industrial radiography, there were no reported cases of overexposure in 1986.

B. LUMINIZING

246. Radioactive materials have been used in luminizing for decades. The practice is still widespread, although the numbers of workers involved is modest. There has, with time, been a move away from the use of radium to tritium and, to a lesser extent, ^{147}Pm. Tritium is used both mixed with a phosphor in paint and as a gas enclosed in phosphor-lined, glass-walled tubes. The data reported in Table 26 are, in general, for luminizing with tritium gas, and the doses arise via internal exposure; the exceptions to this are the data for India, which include exposures to tritium and ^{147}Pm, and the United Kingdom, for which the two components are presented separately.

247. The reported data shown in Table 26 are not comprehensive enough to enable a reliable estimate of the worldwide levels of dose from the luminizing industry, but sums (or averages) of available data are given. At least for those countries reporting data, the overall number of monitored workers in the luminizing industry is small and of the order of a few hundred. The total average annual collective effective dose decreased from about 4 man Sv in the first five-year period to about 1.4 in each of the following periods. Over the same period the overall average annual dose to monitored workers decreased from about 7.4 mSv to about 2.7 mSv. Large reductions also occurred in both of the distribution ratios over this period, with the value of NR_{15} decreasing from about 0.2 to about 0.03 and that of SR_{15} decreasing from about 0.6 to about 0.3.

248. Considerable variation about these overall average values and trends with time is evident in the data for individual countries. With the exception of India, there has been a substantial decrease in the annual collective effective dose in each country; the factor by which dose decreased differed between countries within a range of about 2-4. The average annual doses varied greatly between countries and over time, from about 1 mSv to more than 11 mSv. The annual effective doses, averaged over five-year periods, in both Switzerland and the United Kingdom fell by a factor of about 3 over the period analysed; the dose in India remained relatively constant, while

that in France increased by about 30%. These five-year averages disguise an even greater decrease in the annual doses in the United Kingdom, which fell from about 15 mSv in 1975 to 2 mSv in the late 1980s.

249. The average individual doses in the luminizing industries have, historically, been much larger than those in other industries; this situation still prevails, notwithstanding the major reductions in dose that have been achieved in several countries. The number of workers in the luminizing industries in those countries reporting data was, however, small (about 500); worldwide, the number may be significantly greater, and this aspect warrants further analysis.

C. RADIOISOTOPE PRODUCTION AND DISTRIBUTION

250. Radioisotopes are produced for a great variety of industrial and medical purposes. The main source of occupational exposure in radioisotope production and distribution is external irradiation; internal exposure may be significant in some cases, 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 the practice 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.

251. Worldwide levels of exposure have been estimated from reported national data, with extrapolation within regions based on gross national product. The coverage and scaling of the data were similar to that for industrial radiography. The annual number of monitored workers from worldwide radioisotope production and distribution, averaged over five-year periods, increased from about 60,000 in the first period to about 90,000 in the third period (see Figure XX). This reflects the increasing use of radioisotopes in both industry and medicine. Notwithstanding the increase, the worldwide average annual collective effective dose is estimated to have decreased from about 130 man Sv in the first period to about 100 man Sv in both the second and third periods. About 70% of these collective doses are estimated to have occurred in countries comprising the OECD, with about 20%, at least in the latter two five-year periods, occurring in Eastern Europe.

252. The annual effective 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, with most of the decrease occurring between the first and second periods. This same downward trend is evident in the data for most countries and regional groupings, but there is considerable variation between countries in both the level of the dose and the extent of the decrease. The average dose to monitored workers in different countries and for different periods has varied within a range of 1-9 mSv. The decrease in the average dose over time was less by as much as a factor of 3 in some countries, in others there was essentially no change (in exceptional cases there was even an increase over the period, particularly between the first and second periods).

253. The fraction of the monitored workforce receiving annual doses in excess of 15 mSv is estimated to have decreased from about 0.1 in the first period to about 0.03 in the third; the fraction of the collective effective dose arising from annual doses in excess of the same level is estimated to have changed little over the period, remaining at about 0.2. These fractions were estimated from a smaller set of data than used to estimate collective and individual doses and, as a consequence, are less reliable indicators of worldwide levels.

254. Fewer data are available on average doses to measurably exposed workers than on those to monitored workers, and again no attempt has been made to estimate a worldwide average dose to measurably exposed workers. The reported doses lie, in general, within a range of 2-8 mSv and typically exceed the corresponding doses to monitored workers by a few tens of per cent (and, exceptionally, by factors of 2-3).

255. In the manufacture and processing of radionuclides, there is 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 include doses from intakes of radionuclides; in general, the contribution to the total dose was reported to be a few per cent. All other data on radioisotope production and distribution in Table 26 need clarification in this respect.

D. WELL LOGGING

256. Well logging has been identified in some countries as an occupation that can lead to higher levels of dose than other industrial occupations involving the use of radiation. Both gamma and

neutron sources are used in well logging, but the contribution from each to the reported doses is not generally indicated. Consequently, it has not been possible to transform the reported effective dose equivalents to effective doses. The assumption has been made that the effective dose is equal to the reported effective dose equivalent, while recognizing that this is likely to underestimate the effective dose in so far as the contribution from neutrons is concerned.

257. The data on well logging in Table 26 are not complete enough to enable a reliable estimate of the worldwide levels of dose. Averaged values of the dose to monitored workers and the two distribution ratios are presented in the Table, but summed data are not included because the results could give a misleading picture. The annual dose to monitored workers, from reported data averaged over five-year periods, decreased from about 1.3 mSv to about 1.1 mSv over the period. Somewhat greater proportional reductions are apparent in the distribution ratios over this period, with the value of NR_{15} decreasing from about 0.007 to about 0.002 and that for SR_{15} decreasing from about 0.3 to about 0.04.

258. Variation about these overall average values and trends with time is evident in the data for individual countries. The extent of this variation is, however, less than that observed for other occupations involving the industrial use of radiation. With a few exceptions, the average individual dose to monitored workers in most countries falls within a range of 1-2 mSv. For those countries reporting data on measurably exposed workers, the average annual effective doses typically exceeded those to monitored workers by factors of 2-3; a range of 2-5 mSv encompasses most of the variation in the reported average annual doses to measurably exposed workers.

E. EDUCATION AND RESEARCH

259. Radiation is a research tool in a wide range of disciplines and occupations. It is difficult to make reliable estimates of the levels of exposure in this area, because there is no consistent reporting and few data are identified separately for this category. Data that should rightly be attributed to this category are often aggregated in broad practices of radiation use (e.g. radioisotope manufacture). In many nuclear research establishments, radiation is used for many industrial activities other than support of the commercial nuclear fuel cycle; however, the fraction of exposures arising in the separate activities cannot be readily established.

260. In these circumstances the data in this Section are intended to include only exposures arising in tertiary educational establishments (universities, polytechnics and research institutes with an important educational role) but not those associated with the use of accelerators; data for the latter were in the past often included with those for tertiary education. Notwithstanding this intent, it is unlikely that all of the data in this Section will have been compiled and reported on a truly comparable basis. The data should, therefore, be interpreted with care when comparing them for different countries without further evidence as to their comparability.

261. The data reported by countries are given in the relevant part of Table 26. Worldwide levels of exposures have been estimated from national data by extrapolation within regions based on gross national product. The coverage and scaling of data (by a factor of about 2) were similar to that for industrial radiography. The collective effective dose is less well correlated with gross national product 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.

262. The annual number of monitored workers involved worldwide in the use of radiation in tertiary education, averaged over five-year periods, is estimated to have varied within the range 140,000-180,000 over the whole period (Figure XX). The worldwide average annual collective effective dose is estimated to have decreased from about 70 man Sv in the first five-year period to about 20 man Sv in the third. About 75% of these collective doses are estimated to have occurred in the countries comprising the OECD.

263. The annual effective dose to monitored workers worldwide, averaged over five-year periods, fell from about 0.55 mSv in the first period to about 0.14 mSv in the third, with most of the decrease occurring between the first and second periods. This downward trend is evident in the data for most, but by no means all, of the countries reporting data, but there is considerable variation between countries in both the level of the dose and the extent of the decrease. The average doses were generally a small fraction of a mSv, sometimes a very small fraction, and exceeded 1 mSv only exceptionally. An important reason for this variability is doubtless the adoption of different protocols for who is to be monitored in the respective workforces. The decrease in average dose over time varied by a factor of as much as 3 in some countries; more exceptionally, there were increases in other countries.

264. The fraction of the monitored workforce receiving annual doses in excess of 15 mSv was small and is estimated to have decreased tenfold, from about

0.004 in the first period to about 0.0004 in the third; the fraction of the collective effective dose arising from annual doses in excess of the same level is estimated to have decreased from about 0.2 to about 0.07 over the same period. These fractions were estimated from a smaller set of data than used to estimate collective and individual doses and, as a consequence, are less reliable indicators of worldwide levels.

265. Fewer data are available on average doses to measurably exposed workers than on those to monitored workers, and again no attempt has been made to estimate a worldwide average dose to this group. The average annual doses to measurably exposed workers exhibited much less variability between countries than those to monitored workers and, in general, fell in a range of 0.5-3 mSv.

F. ACCELERATORS

266. 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 purpose; however, the exposures arising from them are more appropriately associated with exposures arising from the medical uses of radiation. Most exposures from accelerators result from induced radioactivity and occur mainly during the repair, maintenance and modification of equipment. These exposures 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. Insufficient information was available to enable doses, reported in terms of effective dose equivalent, to be transformed to effective dose; the simplifying assumption was, therefore, made that they were numerically equal.

267. 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. In 1960-1980, improved beam extraction techniques were developed, which led to reduced levels of activation products; these reductions were, however, largely offset by the continuing increases in beam power.

268. 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.

269. Following from these technical developments and the greater emphasis given generally to ALARA programmes at accelerators, there were large reductions in the annual collective effective doses at major accelerator laboratories between the mid-1970s and mid-1980s [P4]. Decreases in annual collective dose, from about 0.1 to 0.02 man Sv, were experienced at Deutsches Elektronen Synchrotron; from about 0.2 to about 0.02 man Sv at Daresbury Nuclear Physics Laboratory; from about 5 to 1.5 man Sv at European Organization for Nuclear Research and from about 0.5 to about 0.2 man Sv at Lawrence Berkeley Laboratory.

270. The relevant data shown in Table 26 are not complete enough to enable a reliable estimate of the worldwide levels of dose from accelerators, but the sums (or averages) of the available data are shown. It should be noted that these summed or average data largely reflect experience in the United States, which is by far the largest contributor to them. The total average annual collective effective dose has decreased from about 7 man Sv in the first five-year period to about 3.5 man Sv in the third period. Over the same period the overall average annual dose to monitored workers decreased from about 1.6 to about 0.6 mSv. The data on distribution ratios, averaged over those countries reporting data, do not include data for the United States, where most of the collective dose arose, so it would be inappropriate to associate these ratios with either the total numbers of workers or the total collective doses, as they were determined largely by the doses from the United States.

271. Considerable variation about these overall average values and trends with time is evident in the data for individual countries. With the exception of one country, the average annual effective doses to monitored workers all fell within the range 0.3-2.7 mSv. In the United States this dose decreased fourfold, from about 2 to about 0.5 mSv over the period analysed; increases are apparent in some of the other countries.

272. The average annual effective doses to measurably exposed workers exhibit trends similar to those to the monitored workforce. With the exception of one country, these doses fell within the range 1-7 mSv and were typically some two to three times greater than those to the monitored workforce.

G. OTHER INDUSTRIAL USES

273. There are many other uses of radiation in industry, e.g. 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 levels of exposure of workers involved in other uses of radiation are, in general, small. However, because of the way in which they 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 responsible for compiling data to inspect the data periodically. Such inspection is to be encouraged. An indication of occupational exposures from other uses of radiation can be inferred from the difference between the data for all industrial uses worldwide and those for individual occupations for which it was possible to make worldwide estimates.

H. ALL INDUSTRIAL USES OF RADIATION

274. The last section of Table 26 shows the national data on occupational exposures from all industrial uses of radiation grouped together, excluding the nuclear fuel cycle and defence. The data are more complete than for the separate categories of industrial uses of radiation. Worldwide levels have been obtained by regional extrapolation based on gross national product. The sum of gross national products for the countries reporting data was about 50% of the worldwide total in the first five-year period, increasing to about 80% in the third (the countries accounted for about 15% and 30%, respectively, of the world population). On average, therefore, the reported data have been scaled upwards by a factor of about 1.5; there is, however, considerable variation about this average in the scaling for particular regions.

275. The collective effective doses from all industrial uses of radiation in each country reporting data in 1985-1989 are shown in relation to gross national product in Figure XXI. The broad correlation between the two quantities is evident, with the degree of correlation generally increasing when consideration is limited to particular regional or economic groupings of countries. Data on the regional variations of exposures in industrial uses of radiation are summarized in Table 28. The data for the main regions contributing to the collective dose are illustrated in Figure XXII. Direct comparisons should not be made between the normalized doses for the respective periods as they have been derived on different price bases (1977, 1983 and 1989, respectively); appropriate corrections would need to be made to enable direct comparison. Within a given period, a factor of 2-3 encompasses the range of variation in the normalized collective doses between most regions; values for the United States were typically greater by a factor of 2 than those for the rest of the OECD countries.

276. For some countries within a geographical or economic region, the normalized collective dose (normalized in terms of gross national product) 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 industry or that much higher standards of protection had been adopted in those countries. 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.

277. The annual number of monitored workers, averaged over five-year periods, involved with the industrial uses of radiation worldwide is estimated to have varied within the range 500,000-700,000 over the period; the great majority of these workers are employed either in the United States (40%-50%) or in the other countries comprising OECD (30%-40%). The number of workers appears to have increased between the first two periods and then declined in the third (Figure XXII). The average annual collective effective dose was about 900 man Sv in each of the two first periods but decreased significantly in the third to about 500 man Sv; in general, the data for later periods are more reliable because of the smaller degree of extrapolation needed. Roughly equal contributions to this collective dose were made by the United States, the rest of the OECD countries, Eastern Europe and the remainder of the world, although the contribution from Eastern Europe was, in general, smaller than that from the other groupings.

278. The annual effective dose to monitored workers, averaged over five-year periods, fell from about

1.6 mSv in the first period to about 0.9 mSv in the third. This same downward trend is evident in the data for most countries and regional groupings, but there is considerable variation between countries in both the level of the dose and extent of the decrease. For example, average doses to monitored workers vary from as low as 0.1 mSv in some countries (e.g. Finland and Ireland) to as high as 16 mSv in others (the former USSR). Not all countries have provided data on the distribution ratios NR_{15} and SR_{15}. The fraction of monitored workers worldwide receiving annual doses in excess of 15 mSv is estimated from these data to have been about 0.01 in the first five-year period and marginally less in the following two periods. The fraction of the collective dose arising from individual doses in excess of the same level is also estimated to have been fairly constant over the period, about 0.3.

279. Far fewer data are available on average doses to measurably exposed workers than to monitored workers. Most fall in the range 1-5 mSv, but values for several countries fall well outside of this range. Based on these data, the worldwide average annual dose to measurably exposed workers is estimated to have decreased from about 3 mSv in the first two periods to about 2 mSv in the third. Large variations between countries are evident in the ratio of the average dose to measurably exposed and monitored workers. This ratio ranges from about 1 to more than 10; differences in monitoring and reporting practice between countries are probably mainly responsible for this variation. The number of measurably exposed workers is estimated, on a worldwide basis, to be lower by a factor of 2-3 than that of monitored workers. More data on average doses to measurably exposed workers would be useful, as comparisons based on these data are, in general, more reliable than those based on the doses to monitored workers.

280. Some of the variations between countries in the reported statistics undoubtedly arise from differences in how doses are measured and formally recorded, in who in the workforce is to be monitored and in the completeness of the occupations or uses included in the data reported; these aspects warrant closer analysis in future in order to validate comparisons between the data and improve the estimate of worldwide levels of exposure.

I. CUMULATIVE DOSES

281. Few data have been published on cumulative exposures to workers involved with the industrial uses of radiation. Data reported in response to the UNSCEAR questionnaire by Hungary for industrial radiographers are summarized in Table 29 [S8]. The data exhibit, in general, the expected increase in cumulative dose with duration of employment. The average annual increment in dose increases, however, with increasing duration of employment. For those employed or exposed over a period of less than 10 years, the average annual dose was about 4 mSv; for those employed for 15 years the average annual dose was about 7 mSv. Various factors may have contributed to this difference, for example, improvements in practice and radiological standards over time and variations in the type and volume of work undertaken as experience is gained, which will at least be partially correlated with employment duration. About 4% of those employed for more than 10 years had received cumulative doses in excess of 200 mSv; just over 40% of those employed for 14 or 15 years had received cumulative doses greater than 100 mSv.

282. These cumulative doses are broadly comparable with those estimated for contract workers at LWRs in the United States who had at some time in their career been employed at the Calvert Cliffs nuclear power station and are larger than those estimated by the United States Nuclear Regulatory Commission (on the basis of termination records) for all workers at LWRs in the United States. Somewhat larger cumulative doses were experienced at the reprocessing plant at Sellafield in the United Kingdom, at least for those who started working there before the 1970s; for those who started working after that time, the cumulative doses are comparable with those reported here for radiographers.

J. SUMMARY

283. Worldwide exposures from industrial uses of radiation are summarized in Table 30. Estimates have been made for industrial uses as a whole and separately for industrial radiography, for radioisotope production and distribution and for tertiary education and research institutes. By subtracting the data for these separate categories from those for "all industrial activities" given in Table 26, estimates have been made of worldwide doses for "other" industrial uses; these other industrial uses also include doses from those occupational categories that were analysed separately in this Chapter but for which it was not possible to make worldwide estimates (i.e. the luminizing industry, well logging and accelerators). The number of workers and average annual individual and collective doses for these categories are illustrated in Figure XX.

284. Of the average annual number of monitored workers involved worldwide with the industrial uses of radiation (ranging from about 550,000 to 700,000 over the period analysed), about 16%, 13% and 27% are

estimated to have been employed in industrial radiography, isotope production and distribution and tertiary education, respectively. Typically, about 40% or more were assigned to the category of "other".

285. The average annual collective effective dose worldwide from all industrial uses has decreased from about 900 to about 500 man Sv over the period analysed. On average about 25% of the total collective dose arose in industrial radiography, about 14% in isotope production and about 6% in tertiary education. On average more than 50% of the total collective dose occurred in other industrial uses of radiation.

286. The average annual doses to monitored workers in industrial radiography exceeded the average doses from all industrial uses by about 50%. Those in isotope production also exceeded the averages for all industrial uses but to a lesser extent and not in all periods; the doses from tertiary education were, in general, smaller than the overall average doses by factors of 3-6, depending on the period. There is much variation between the values of the distribution ratios NR_{15} and SR_{15} for all industrial uses and the particular occupational categories; those for industrial radiography are invariably greater and those for tertiary education smaller than those for all industrial uses. In general, for each occupational category, the ratio, NR_{15}, was observed to decrease with time; the ratios, SR_{15}, however, with the exception of that for tertiary education, varied little over the period analysed.

V. MEDICAL USES OF RADIATION

287. Radiation is used in medicine for both diagnostic and therapeutic purposes. Its wide range of applications and the types of procedures or techniques employed in the context of patient exposure are reviewed in Annex C, "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 radiography, dental practice, nuclear medicine (diagnostic and therapeutic), radiotherapy and all medical uses of radiation (for human purposes) grouped together. In addition, separate consideration is given to exposures in veterinary medicine.

288. 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 different 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. There is considerable potential for drawing erroneous conclusions as a result of the direct and unqualified comparison of data in this area. The reasons for this were already pointed out. They include differences in monitoring and recording practice, in defining the workforce to be monitored, in minimum detectable levels and in the recording of doses less than the minimum detectable level. More important in the medical field, however, are differences in where dosimeters are located (in particular, whether they are above or below lead aprons when these are worn). Further complicating factors are the non-uniformity and low energy of the radiation that contributes most to the overall occupational exposures from the medical uses of radiation in such circumstances; the approach used to derive effective doses from dosimeter measurements can have major implications for the comparability of occupational exposures.

289. To assist in the interpretation and/or qualification of the statistics reported in this Chapter, the main features of the dose monitoring and reporting procedures adopted in each of the countries that have responded to the UNSCEAR Survey of Occupational Exposures in Medicine are summarized in Table 31. Significant differences are evident, in particular in the location of the dosimeter (above or below the lead apron) and whether the direct dosimeter reading or some corrected value was entered into the formal dose record. Other important differences that may influence the comparability and/or accuracy of reported statistics are the minimum detectable levels of the various dosimeters and the manner in which doses less than this level or levels are recorded. These differences must be recognized when comparing the data presented in the following Sections.

290. Notwithstanding these qualifications and reservations, it proved impracticable in this analysis to revise or normalize the reported exposures to ensure that fair comparisons could be made between them. 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.

291. National data on medical uses of radiation, categorized as diagnostic radiography, dental practice, nuclear medicine, radiotherapy, veterinary medicine and all (human) medical uses of radiation grouped together and averaged, where possible, over five-year periods, are given in Table 32. Worldwide levels of exposure have been estimated from these national data by extrapolation within particular regions based on gross national product as described in Section I.C. In general, the collective dose for each practice was well correlated with gross national product, but there were exceptions for some countries. The degree of extrapolation needed varied with the medical use considered but was typically within a range of about 2 to 7 overall; there was, however, considerable variation about these average values for particular regions or periods.

292. The data on exposures from medical uses of radiation for the United States have been considered seprately from the remainder of the OECD region because of the major contribution to worldwide exposures from this country and the much larger collective dose per unit gross national product. Data for the United States have been reported separately for all medical uses of radiation and for dental radiography; the levels of exposure from diagnostic radiography, nuclear medicine and radiotherapy, taken together, can thus be estimated by simple subtraction of exposures from dental radiography from those for all medical uses. Assumptions must be made, however, on the attribution of this residual dose between the respective uses. In the absence of other indications, the distribution between the three uses was assumed to be the same as that on average for OECD countries (or, more strictly, those reporting data).

A. DIAGNOSTIC RADIOGRAPHY

293. The estimation of occupational exposures from diagnostic radiography is complicated by the fact that the radiation comes largely from point sources fairly close to the workers and is in general of very low energy. Exposure is very non-uniform because of the inverse square law and attenuation in the body. Matters are further complicated by the fact that dosimeters are not always worn at the same location, although they are commonly worn at the waist or neck. Consequently, the effective dose is difficult to infer from a single personal dosimeter reading, especially if the dosimeter is not in the primary radiation field striking the body. For a reliable estimate to be made, detailed information on the circumstances of the exposure and the nature of the radiation are needed. Because of these difficulties, the direct dosimeter reading is commonly used in formal dose records as a surrogate for the effective dose. The compilation of reliable statistics in this area is further hampered by the fact that many of the exposures are close to the minimum detectable level of the dosimeter. Differences in MDLs for various dosimeters and in the protocols for recording doses below these may therefore adversely affect the reliability of the data and compromise the validity of direct comparisons between statistics compiled in different ways.

294. It was judged in the UNSCEAR 1988 Report [U1] that for radiation qualities used in diagnostic x-ray procedures, the dosimeter usually gives a reading that is 2 to 4 times higher than the effective dose if no protective apron is worn and if the exposure is relatively uniform. If a protective apron is worn and the personal dosimeter is placed on the outside, then the dosimeter reading could be as much as 10-20 times higher than the effective dose. It can be seen from Table 31 that in most cases, at least where the information is available, the direct dosimeter reading is entered into formal dose records. The data given may thus be considerable overestimates, particularly for those countries where lead aprons are worn and dosimeters placed above them. Significant differences are also evident in Table 31 in the minimum detectable levels of the dosimeters used and in the assignment of doses when dosimeters are lost; these differences must be recognized when comparing data for the respective countries.

295. Countries reporting data on occupational exposures from diagnostic radiology comprised about 13% of the total gross national product worldwide in the first five-year period increasing to about 18% in the third. On average, therefore, the reported data have been scaled upwards by a factor of about 7; there was, however, considerable variation about this average in the scaling for particular regions.

296. The annual number of monitored workers, averaged over five-year periods, involved worldwide in diagnostic radiography approximately doubled, from about 0.63 to 1.4 million over the period analysed (see Figure XXIII); the great majority of these workers (about 70%) were employed in those countries comprising the OECD. The annual worldwide collective effective dose, averaged over five-year periods, was about 600 man Sv in the first period increasing to about 760 man Sv in the third period. About 75% of the worldwide collective dose occurred

in countries of the OECD in the first period; this proportion dropped to about 60% in the third period.

297. The annual effective dose to monitored workers worldwide, averaged over five-year periods, fell from about 0.9 mSv in the first period to about 0.6 mSv in the third. This same downward trend is evident in the data for most countries and regional groupings, but there is considerable variation between countries in both the level of the dose and the extent of the decrease. Most average annual doses fall in the range 0.1-1 mSv, but somewhat higher values are reported for China, Indonesia and, in particular, Peru. In practice, all of the above doses, both individual and collective, may be considerable overestimates, as it was generally assumed that the dosimeter reading could be equated with effective dose.

298. The fraction of the monitored workforce worldwide receiving annual doses in excess of 15 mSv was small and estimated to have been about 0.003 over the first two periods, with an apparent increase to about 0.005 in the third period; the fraction of the worldwide collective effective dose from annual doses in excess of the same level was about 0.1 in the first period, decreasing to about 0.05 in the second period with an apparent increase to about 0.2 in the third period. Undue significance should not, however, be assigned to these apparent increases in the third period. These increases are due to data for China only being reported for the third period and the somewhat higher values of the distribution ratios reported for this country. For those countries reporting data for the whole period analysed there is evidence, overall, of a small downward trend with time in the values of both ratios.

299. Fewer data are available on average annual doses to measurably exposed workers than to monitored workers, so no attempt has been made to estimate a representative worldwide level. Most doses fall in the range 1-5 mSv, but a few fall well outside of this range (e.g. 11 mSv for China in 1985-1989). The percentage of monitored workers who are measurably exposed varies considerably between countries, from about 5% to almost 90%. Large variations between countries are evident in the ratio of the average dose to measurably exposed and monitored workers. This ratio ranges from about 1 to more than 10; differences in monitoring and reporting practice are probably mainly responsible for the variation.

B. DENTAL PRACTICE

300. Worldwide levels of dose and numbers of workers in dental practice have been estimated from national data by extrapolation within particular regions based on gross national product. The sum of the gross national products for those countries reporting data was about 50% of the worldwide total in the first five-year period, increasing to about 60% in the third. On average, therefore, the reported data have been scaled upwards by a factor of about 2 but with considerable variation about this average value for particular regions.

301. The annual number of monitored workers, averaged over five-year periods, in dental practice worldwide is estimated to have increased from about 400,000 to about 500,000 over the period analysed (see Table 32 and Figure XXIII); more than half these workers were employed in the United States. The average annual collective effective dose was about 120 man Sv in the first period, decreasing to about 25 man Sv in the third, with most of the decrease occurring between the second and third periods. The overall trend largely reflects that in the United States, where the annual collective dose is reported to have decreased over the same period, from about 80 to 12 man Sv. In other countries the downward trend was less pronounced, not evident at all or, occasionally, reversed.

302. The annual effective dose to monitored workers worldwide, averaged over five-year periods, fell progressively from about 0.3 mSv in the first period to about 0.05 mSv in the third, again largely reflecting experience in the United States, which makes a dominant contribution to the total reported. While this same downward trend is evident in most, but not all, countries and regions, there is considerable variation in both the level of the dose and the extent of the decrease for particular countries or regions.

303. The fraction of the monitored workforce (summed over the reported data) receiving annual doses in excess of 15 mSv was very small and is estimated to have varied within the range 0.0003-0.0008 over the three periods; the fraction of the collective effective dose (summed over the reported data) estimated to arise from annual doses in excess of that level varied over a range of about 0.08-0.12. Because the data are incomplete (i.e. no data reported for some countries and for limited periods in other cases), these ratios are not reliable indicators of worldwide levels of these quantities nor of trends in their values. The most that can be concluded from them is that, in general, the fraction of dental workers receiving an annual dose in excess of 15 mSv is very small, i.e. significantly less than one in a thousand workers.

304. Fewer data are available on average annual doses to measurably exposed workers than to monitored workers. Most fell within the range 0.2-3 mSv, but there were exceptions. The proportion of monitored

workers who were measurably exposed varied between countries from a few per cent to essentially 100%; this is indicative of differences in practice with regard to who is monitored and in the reporting and recording of doses, which may partially explain some of the wide variation in reported average individual doses to both monitored and measurably exposed workers.

C. NUCLEAR MEDICINE

305. Over the past decade there has been a rapid expansion in the use of nuclear medicine. Many radionuclides are used to label the pharmaceuticals, but the two most important are ^{99m}Tc and ^{131}I. Preparation and administration of pharmaceuticals are significant contributors to overall levels of exposure. Moreover, as they are administered by injection, relatively high doses to the hands of the workers are also possible. Generally, lead shielded syringes are recommended, but they are not always used. Following injection, the patient is another source of exposure for the medical staff. Internal exposures of workers may also occur, but few data have been reported on their relative contribution. Radiopharmaceuticals are also used in therapy, and the main sources of occupational exposure are the same as in diagnostic use. Since the data on occupational exposures arising in nuclear medicine rarely distinguish between diagnostic and therapeutic applications, this analysis is directed to overall levels of exposure in the field. Consideration is limited here to effective doses to which extremity doses do not contribute. Because of the potential for significant extremity doses in nuclear medicine, these would merit attention in any future analysis.

306. Worldwide levels of dose and numbers of workers involved in nuclear medicine have been estimated from national data using the same extrapolation procedures as described previously. The sum of the gross national products for those countries reporting data was about 12% of the worldwide total in the first five-year period increasing to about 18% in the third. On average, therefore, the reported data have been scaled upwards by a factor of about 7 but with considerable variation about this average value for particular regions.

307. The annual number of monitored workers, averaged over five-year periods, in nuclear medicine worldwide is estimated to have increased from about 60,000 to about 90,000 over the period analysed (see Table 32 and Figure XXIII); more than half of these workers were employed in countries of the OECD. The average annual worldwide collective effective dose was about 60 man Sv in the first five-year period, increasing to about 90 man Sv in each of the following two periods. The annual effective dose to monitored workers worldwide, averaged over five-year periods, was about 1 mSv and varied little over the whole period analysed. A downward trend is evident for some countries and regions, but there is considerable variation between countries in both the levels of dose and the trends. Most average annual doses fell in the range 0.2-2 mSv, but there are exceptions to this generalization, in particular for Mexico and Peru, where somewhat higher doses were experienced in some periods.

308. The fraction of the monitored workforce worldwide receiving annual doses in excess of 15 mSv was small and is estimated to have been about 0.002 for the first two five-year periods with an apparent increase to about 0.004 in the third period; the fraction of the worldwide collective effective dose from annual doses in excess of the same level was about 0.09 in the first period, decreasing to about 0.03 in the second period with an apparent increase to about 0.1 in the third period. Undue significance should not, however, be assigned to these apparent increases in the third period. These increases are due to data for China only being reported for the third period and the somewhat higher values of the distribution ratios reported for this country. For those countries reporting data for the whole period analysed there is evidence, overall, of a small downward trend with time in the values of both ratios.

309. Fewer data are available on average annual doses to measurably exposed workers than to monitored workers, so no attempt has been made to estimate worldwide levels for this quantity. Most doses were between 1 and 4 mSv, but some were considerably greater (e.g. 13 mSv in China in one period). The proportion of monitored workers who were measurably exposed varied from a few per cent to essentially 100%; this is indicative of differences in practice with regard to who is monitored and in the reporting and recording of doses, which may partially explain some of the wide variation in reported average individual doses to both monitored and measurably exposed workers.

D. RADIOTHERAPY

310. Occupational exposures during the practice of radiotherapy come from several sources. In general, the rooms in which external beam radiotherapy is practised are very well shielded, and the staff receive little exposure. An exception to this occurs with either neutron beams or electron accelerators operating above 10 MeV. The neutrons activate nearby materials,

which then constitute a source of radiation and exposure to the workers even after the primary beam has been turned off. In such cases, about 75% of the exposure is due to photoactivation products in the treatment head [U1], and the remainder is due to other activation products in the room; induced activity in the patient is not a significant source.

311. An important source of occupational exposure from radiotherapy is brachytherapy, which often involves the insertion or surgical implantation of radio-active wires, needles or seeds. Preloaded surgical applicators are also sometimes used. There has, however, been a trend in countries with a high level of health care towards the use of after-loading devices, whenever possible, to reduce occupational exposures. This involves the prepositioning of an applicator or holder on or in the patient and the insertion of the radioactive material at a later time. The occupational dose from brachytherapy is very dependent on whether the source insertion is manual or automated in some manner. Once the sources have been inserted, the patient becomes a source of exposure to the medical staff. Because brachytherapy contributes significantly to medical occupational exposures, it should be analysed separately. Since, however, few data have been separately reported on brachytherapy, the analysis of exposures has been carried out for radiotherapy as a whole.

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

313. The annual number of monitored workers, averaged over five-year periods, in radiotherapy worldwide is estimated to have increased from about 80,000 to about 110,000 over the period analysed (see Table 32 and Figure XXIII); more than half of these workers were employed in countries of the OECD. The average annual worldwide collective effective dose is estimated to have been reduced by almost half from about 190 man Sv in the first period to about 100 man Sv in the third period, with the decrease occurring mainly between the second and third periods. The annual effective dose to monitored workers worldwide, averaged over five-year periods, fell from about 2.2 mSv in the first period to about 0.9 mSv in the third. This downward trend is evident in many but by no means all countries and regions, and there is considerable variation in both the level of the dose and the extent of the decrease for particular countries or regions. Most average annual doses fell between 0.5 and 2 mSv, but there were exceptions to this generalization, in particular in Finland, where the doses were much lower, and in Mexico and especially Peru, where they were significantly higher.

314. The fraction of monitored workers, averaged over the reported data, receiving annual effective doses in excess of 15 mSv was small and is estimated to have decreased from about 0.012 in the first period to about 0.008 in each of the subsequent periods. The corresponding fractions of the collective effective dose arising from annual doses in excess of that level were about 0.3 in the first period, decreasing to about 0.2 in the subsequent periods. Since the data for most countries generally exhibit the same trends, these average values can be used to provide a rough estimate of worldwide levels for these quantities.

315. Fewer data are available on average annual doses to measurably exposed workers than to monitored workers. Most fell between 1 and 5 mSv, but there were some exceptions, for example in China, where the reported dose for one period was 10 mSv. The proportion of monitored workers who were measurably exposed varied from less than 10% to essentially 100%; the variation reflects differences in practice with regard to who is monitored and in the reporting and recording of doses, which may partially explain some of the wide variation in reported average individual doses to monitored and measurably exposed workers.

E. ALL MEDICAL USES OF RADIATION

316. National data on occupational exposures from all medical uses of radiation, averaged over five-year periods, are given in the last section of Table 32. Worldwide levels of exposure have been estimated from the reported data by extrapolation based on gross national product. In Figure XXI, the collective effective doses from all medical uses of radiation in each country reporting data in 1985-1989 are shown in relation to the gross national product. The broad correlation between the two quantities is evident, with the degree of correlation generally increasing when consideration is limited to particular regional or economic groupings of countries.

317. For some countries in a geographical or economic region, the normalized collective dose (normalized in terms of the gross national product) 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 data are good surrogates for effective dose.

318. The data on occupational exposures from all medical uses of radiation are presented for various geographic regions and economic groupings in Table 33. 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 and 1989, 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 exceptions to this generalization are the United States, where the normalized collective dose is some two to three times that for the remainder of the OECD, and Latin America and Asia where the normalized collective doses are substantially less.

319. The exposure data for the major regional groupings of countries are illustrated in Figure XXIV. The worldwide annual number of monitored workers, averaged over five-year periods, is estimated to have increased from about 1.3 to about 2.2 million over the period; the majority of these workers are employed in the United States or in countries comprising the rest of the OECD. The average annual collective effective dose was about 1,000 man Sv in the first and third periods with evidence of an increase of about 10% in the intermediate period; in general, the data for later periods are more reliable because of the smaller degree of extrapolation needed. Notwithstanding this relatively unchanged level of worldwide exposure over the period analysed, somewhat greater changes occurred in particular regions. The significant decrease in the average annual collective dose in the United States and the increase in that from the rest of the world, excluding Eastern Europe and the OECD, are apparent. Half or more of the worldwide collective dose occurs in countries of the OECD, although this contribution has decreased with time.

320. The annual effective dose to monitored workers worldwide, averaged over five-year periods, fell from about 0.8 mSv in the first period to about 0.5 mSv in the third. This same downward trend is evident in the data for most countries and regional groupings, but there is considerable variation between countries in both the level of the dose and extent of the decrease. The average annual doses, and their rate of decline, were broadly comparable in Eastern Europe and in the OECD (excluding the United States); somewhat higher levels of average individual dose have been reported for the United States. No undue significance should be attached to the variation in individual doses illustrated for those countries depicted as the "remainder" in Figure XXIV; any trends in these data will have been distorted because different countries were included in this category in the different time periods. The average annual doses reported by individual countries vary over a considerable range, for example from as low as 0.1 mSv in some countries for some periods (e.g. Germany, Ireland and Switzerland) to as high as a few millisievert in others (e.g. China, Mexico and Peru).

321. The fraction of the monitored workforce worldwide receiving annual doses in excess of 15 mSv was small and is estimated to have decreased from about 0.003 in the first period to about 0.002 in the second with an apparent increase to about 0.009 in the third period; the fraction of the worldwide collective effective dose from annual doses in excess of the same level was about 0.14 in the first period, decreasing to about 0.10 in the second period with an apparent increase to about 0.24 in the third period. The apparent increases in the third period are due to the inclusion of the data for China, which had been reported only for this period. For those countries reporting data for the whole period analysed there is evidence, overall, of a small downward trend with time in the values of both ratios.

322. Few data are available on average doses to measurably exposed workers than to monitored workers. Most fell in the range 1-5 mSv, but values for several countries are well outside of this range (10 mSv for China in 1985-1989). Based on these reported data, a worldwide average annual effective dose of about 1.6 mSv has been estimated as generally applicable over the entire period. Large variations between countries are evident in the ratio of the average dose to measurably exposed and monitored workers. This ratio ranges from about 1 to more than 10; differences in monitoring and reporting practices between countries are probably mainly responsible for this variation. More data on average doses to measurably exposed workers would be useful, as comparisons made on this basis are, in general, more reliable than those made on the basis of the dose to monitored workers.

323. Some of the variation between countries in the reported statistics undoubtedly arises from differences

in how doses are measured and formally recorded, in who in the workforce is to be monitored and in the completeness of the occupations or uses included in the data reported; these aspects warrant closer analysis in future in order to validate comparisons between the data and improve the estimate of worldwide levels of exposure. For example, had data been available for China for the entire period, it is likely that the estimated worldwide values of the two distribution ratios would have shown a downward trend with time, but their absolute levels would have been greater than indicated above, at least for the first two periods.

F. VETERINARY PRACTICE

324. Diagnostic radiography is the main source of occupational exposure in veterinary practice. The annual number of monitored workers, averaged over five-year periods, worldwide is estimated to have increased threefold, from about 50,000 to about 160,000 over the period analysed (see Table 32 and Figure XXIII); more than 70% of the workers were employed in OECD countries. The average annual worldwide collective effective dose is estimated to have increased twofold, from about 25 man Sv in both the first and second periods to about 50 man Sv in the third period. The annual effective dose to monitored workers worldwide, averaged over five-year periods, fell progressively from about 0.5 mSv in the first period to about 0.3 mSv in the third, although there was considerable variation about these values in the doses for individual countries (most fell in the range 0.1-0.8 mSv). These trends in dose and in the number of monitored workers are largely a reflection of experience in the United States, given its very large contribution to the sum of the reported data. Indeed, while a downward trend in individual dose is evident in many countries, it is not evident in all, and the extent of the decrease is, in general, less pronounced than that in the United States.

325. The fraction of monitored workers, averaged over the reported data, receiving annual effective doses in excess of 15 mSv was very small and is estimated to have decreased from about 0.001 in the first period to about 0.0001 in each of the subsequent periods. The corresponding fractions of the collective effective dose arising from annual doses in excess of the same level were about 0.1 in the first period decreasing to about 0.02 in the subsequent periods. These average values are based on insufficient data for them to be judged truly representative of worldwide levels; at best they can be considered as indicative of such levels.

326. Fewer data are available on average annual doses to measurably exposed workers than to monitored workers. Most fell in the range 0.5-2 mSv, but there were some exceptions to this. The proportion of monitored workers who were measurably exposed varied from about 10% to about 50%, owing to differences in practice with regard to who is monitored and in the reporting and recording of doses, which may partially explain some of the wide variation in reported average individual doses to both monitored and measurably exposed workers.

F. SUMMARY

327. Worldwide exposures from the medical uses of radiation for treatment of humans (i.e. excluding veterinary practice) are summarized in Table 34. Worldwide estimates have been made for diagnostic radiography, dental practice, nuclear medicine and radiotherapy, and for all medical uses of radiation. The annual number of monitored workers involved worldwide, averaged over five-year periods, increased from about 1.3 million in the first period to about 2.2 million in the third. Averaged over the whole period, approximately 65% of these workers were involved with diagnostic radiography, 25% with dental practice, 4% with nuclear medicine and 6% with radiotherapy.

328. The worldwide annual collective effective dose, averaged over five-year periods, remained relatively uniform over the whole period, at about 1,000 man Sv. There is evidence that the dose was about 10% greater in the second period than in the first and third periods. This estimate of 1,000 man Sv is lower by a factor of 4 to 5 than the estimate in the UNSCEAR 1988 Report [U1], which was 1 man Sv per million population. The present estimate is based on much more extensive reported data. Even so, it may itself be an overestimate of the worldwide collective dose (doses from diagnostic radiography, which makes by far the greatest contribution to the reported collective dose from all medical uses of radiation, are suspected to have been overestimated).

329. Over the three periods, there appear to have been significant changes in the contribution of different practices to the total collective dose. The contribution of diagnostic radiography is estimated to have increased from 60% to 80% between the first and third periods, whereas that from dental practice decreased from 12% to 3%. The contribution from nuclear medicine increased from about 6% to about 9% over the whole period, whereas that from radiotherapy decreased from about 20% to 10%.

330. The average annual effective doses to monitored workers involved in medical uses of radiation and the doses to monitored workers in each of the main

categories of medical use of radiation all decreased with time, even if by differing amounts. This is apparent in Figure XXIII, where the trends in separate practices are indicated. Radiotherapy has, in general, resulted in the largest average annual doses (about 2.2 mSv decreasing to about 0.9 mSv between the first and third periods), typically exceeding the average for all medical uses by a factor of about 2-3. The average annual doses from nuclear medicine (remaining at about 1 mSv over the whole period) also exceeded the overall averages but to a lesser degree. The average annual doses from diagnostic radiography (about 0.9 mSv decreasing to about 0.6 mSv) were broadly comparable with the averages for all medical uses, whereas those for dental radiography (about 0.3 mSv decreasing to about 0.05 mSv) were much lower. The doses from both diagnostic and dental radiography may, however, be significant overestimates because the dosimeter reading is generally used directly as a measure of effective dose.

331. The fraction of monitored workers worldwide exposed to annual effective doses in excess of 15 mSv is small for each medical practice and for medicine overall. Typically, a small fraction of 1% of workers receive annual doses in excess of this level. The values of this quantity (NR_{15}) are somewhat greater for radiotherapy, and those for dental radiography somewhat lower, than the average for all medical practices. The fraction of the collective dose arising from individual doses in excess of that level has varied significantly between practices within an overall range of about 0.03 to about 0.3; the larger values are generally associated with radiotherapy. For all medical uses of radiation the value of NR_{15} decreased from about 0.003 in the first period to about 0.002 in the second, increasing again in the third to about 0.009. The value of SR_{15} followed the same trend, decreasing from about 0.18 to about 0.12 between the first and second periods and then increasing to about 0.24. These increases in the third period, however, are more apparent than real. They are mainly due to the somewhat higher values for China having been reported only for the third period. For those countries reporting data for the whole period analysed there is evidence, overall, of small downward trends with time in both distribution ratios.

332. The variation in occupational exposures from all medical uses of radiation between different geographic or economic regions is summarized in Table 33 and illustrated for selected regions in Figure XXIV. Averaged over the whole period, 33% of monitored workers worldwide are estimated to have been in the United States, with a similar percentage in the rest of the OECD. In Eastern Europe (including the former USSR) the estimated proportion is 20%; based on less complete data, about 4% are estimated to be in Latin America and 4% in countries with centrally planned economies in Asia. About 1% of the total workforce is estimated to be on the Indian subcontinent and a similar proportion in south and south-east Asia (non-centrally planned economies).

333. The contribution of the United States to the worldwide annual collective effective dose almost halved over the period analysed, decreasing from about 46% to 27%. Averaged over the same period, the contribution of the rest of the OECD was about 20% and that of Eastern Europe about 12%. Based on less comprehensive data, Latin America and countries with centrally planned economies in Asia each contributed about 20%, at least in the more recent five-year periods. The Indian subcontinent and south and south-east Asia (non-centrally planned economies) each contributed about 1%, and there is evidence of a significant increase in the contribution of the latter to about 3% in the most recent five-year period.

334. The data on average individual doses to monitored workers indicate that, in general, the doses in the OECD (excluding the United States) and Eastern Europe were less than the worldwide averages for the respective periods. Those for Asia and Latin America were, in general, significantly in excess of the average, while those in the United States and on the Indian subcontinent were, broadly, of the same magnitude.

335. Normalized collective doses (normalized in terms of both gross national product and population) for individual regions, averaged worldwide, are summarized in Table 33. Significant variation is evident between the various values, with the range of variation being far smaller when the normalization is carried out in terms of gross national product as opposed to population size. In terms of population, the normalized collective doses for particular regions vary over more than two orders of magnitude, from about 0.01 to about 2 man Sv per million people, with a worldwide average of about 0.2 man Sv per million people (compared with a representative value of 1 man Sv per million people assumed in the UNSCEAR 1988 Report [U1]). When expressed in terms of gross national product, the collective doses vary over less than an order of magnitude, and with a few exceptions, the variation is much less than this. A number of trends are apparent in these normalized doses: those for the United States are generally greater than those for the rest of the OECD by a factor of 2-3; those for the rest of the OECD, Eastern Europe and the Indian subcontinent are broadly of the same magnitude; and those for Latin America and the centrally planned economies in Asia are substantially in excess of the worldwide averages of this quantity.

VI. NATURAL SOURCES OF RADIATION

336. All workers are inevitably exposed to natural sources of radiation in the course of their work. With the exception of a few occupations, their exposures to natural radiation do not differ significantly from the general background. In the UNSCEAR 1988 Report [U1], a relatively comprehensive assessment was made of available data on exposures in those occupations or industrial practices where enhanced levels of exposure to natural sources of radiation might be experienced. Estimates were made of doses to aircrew, workers at coal-fired power stations, underground miners and workers involved with the industrial and agricultural uses of phosphates (but not with their mining). Underground mining was estimated to make by far the greatest contribution to the overall collective dose from occupational exposure to natural sources of radiation. These estimates are updated here, with emphasis given to those occupations or practices contributing most to the collective dose and to areas where significant new data have since become available. Exposures to natural sources of radiation from the mining and subsequent processing and use of uranium have already been evaluated in the context of the nuclear fuel cycle and are not considered further here.

A. EXTRACTIVE INDUSTRIES

337. The extraction and processing of earth materials increase the exposure of workers to natural sources of radiation. The general public may be somewhat exposed from the subsequent utilization of the products or by the disposal of wastes. The extractive industries include all forms of mining; attention is focused here on underground operations, where radon exposures are greatest.

1. Underground mining

338. Mining is an extensive industry. As can be seen in Table 35, there are about 4.7 million underground miners worldwide, with 84% engaged in coal mining and 16% in the mining of other minerals [C2]. Among the latter group are about 90,000 engaged in the mining of uranium ores (see Table 3). China is the largest employer of workers in coal mines and South Africa in other mines (mainly gold mines). The numbers of workers listed in Table 35 are estimates for 1991. In addition to the inherent uncertainties in the data, such estimates can fluctuate widely from year to year owing to continually changing regional and global economic conditions.

339. Exposures in underground mining may arise from external and internal sources; the main contributors to internal exposure are the inhalation of radon and thoron progeny and the inhalation of dust containing long-lived alpha emitters of the uranium and thorium series. The relative contribution of each will depend on the type of mine, the geology and the working conditions, particularly the degree of ventilation. 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, in general, their quality or reliability is much less than that of 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; considerable errors in dose estimates can occur when they are based on grab samples of air instead of personal air samplers. This situation is, however, changing, and more comprehensive and reliable data can be expected in the future.

340. Data on exposures to radon and its decay products in about 1,200 underground mines are summarized in Table 36; the data are presented separately for coal and other (excluding uranium) mines. Considerable variation is evident in the average levels of exposure reported between countries. There is also considerable variation between doses at mines within a given country. This is indicated in Table 37, where average individual doses are given for mines in the United States and the former USSR; it should be noted that the tabulated doses differ from those reported in the respective references, in particular a conversion factor of 5.6 mSv WLM^{-1} has been assumed in contrast to a value of 10 mSv WLM^{-1} in the data reported. Data have also been reported for coal and other mines in China [P5, X1]; for non-coal mines, the reported average annual doses are typically more than an order of magnitude greater than the average values reported for other countries. These data for non-coal mines [P5, X1] are not, however, thought to be representative of China as a whole for two reasons: first, the reported values are based on a limited number of grab samples which may not be representative of the conditions experienced by the whole workforce and, secondly, the data are for mines in only one province of China [P6].

341. The data in Table 36 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 enough 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, which are summarized in Table 38; these doses can be considered broadly representative for the latter half of the 1980s. The doses were estimated as the sum, over all 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 applicable worldwide. A conversion factor of 5.6 mSv WLM^{-1} has been assumed in estimating effective doses from the exposures reported in Table 36.

342. The worldwide annual collective effective dose from the inhalation of radon progeny in underground mines (excluding uranium mining) is estimated to be about 5,300 man Sv, with about 1,500 man Sv (about 30%) arising in coal mines and about 3,800 man Sv (about 70%) in other mines. About 30% of the worldwide collective dose from coal mining arose in Poland and about 10% in the former USSR. In other mines, excluding uranium mines, about 50% of the worldwide collective dose occurred in South Africa. The worldwide average annual effective dose was estimated to be about 0.4 mSv in coal mines and about 5 mSv in other mines.

343. 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 38 from the inhalation of radon progeny alone are underestimates of 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 [P1] suggest that the contribution from other pathways is about 1 mSv per annum which, except in coal mines, is a small fraction of the dose from radon progeny. In the absence of better data, the annual doses given in Table 38 for radon progeny have been increased by 1 mSv to take account of other exposure pathways. When such an allowance is made, the annual collective effective dose from all exposure pathways for coal mining worldwide becomes about 5,400 man Sv and that from other mining (excluding uranium) about 4,500 man Sv. The corresponding average annual effective doses from all pathways are about 1.4 mSv and 6.4 mSv for coal and other mines, respectively.

344. The doses estimated in the above manner represent exposures received while 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 enable 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. This estimate 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 A, "Exposures from natural sources of radiation").

345. 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 latter half of the 1980s, is estimated to have been about 7,500 man Sv; about one half of this total collective dose arose in coal mining with the other half arising in other mines (excluding uranium). For comparison, the annual collective dose from uranium mining (see Table 3), averaged over the period 1975-1989, was about 1,300 man Sv. Of those countries identified separately in Table 38, South Africa (about 27%) makes the largest contribution to the total collective dose with significant contributions also from the former USSR (about 11%) and Poland (about 7%). The additional worldwide average annual effective dose received by underground miners from their work is estimated to have been about 0.9 mSv in coal mines and about 6 mSv in other mines (excluding uranium), although there was considerable variation about these averages between countries and between mines in a given country. Somewhat greater individual and collective doses are likely to have been received before the latter half of the 1980s, because less attention was paid to the control and reduction of exposures from this source. Insufficient data are available, however, to make a reliable estimate of how much greater they might have been; the few data in Table 36 suggest that they may have been substantially greater.

346. Very approximate and tentative estimates were made in the UNSCEAR 1988 Report [U1] 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 the very approximate nature of this earlier estimate and the change adopted here in the conversion factor for exposure to radon progeny, it compares favourably with the current estimate of about 3,400 man Sv. A very rough estimate of 20,000 man Sv was also made in [U1] for the annual collective effective dose from underground mining

apart from coal and uranium; this earlier 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 exceeds the present estimate, of about 4,100 man Sv, by a factor of about 5. Differences in the number of miners (about a factor of 3 lower than before) and in the average individual dose (about a factor of 2 lower than before) are responsible for the decrease in the collective dose estimated previously. For all underground mining (but excluding uranium) the collective dose estimated here (about 7,500 man Sv) is about a factor of 3 less than that estimated in the UNSCEAR 1988 Report [U1].

2. Surface mining

347. Mineral sands are mined and processed in several countries. Monazite, an important constituent of the sands, has concentrations of thorium of about 2.5 10^5 Bq kg^{-1} and concentrations of uranium an order of magnitude less. Surface mining is followed by a wet and then a dry processing stage. The important pathways of exposure are external irradiation from gamma-ray emitting radionuclides of the ^{232}Th and ^{238}U decay series and inhalation of ore dust, the latter being quite pronounced at the dry stage. Exposure and employment information are scarce. Data for Western Australia, a major producer of monazite, show that dry-process workers received appreciable doses from the inhalation of dust [H6]. Annual effective doses for 376 dry-process workers averaged 20 mSv for 1983-1988, with 50% of workers above 15 mSv. About 90% of the dose is from internal exposure. For all categories of workers (1,318 in number), the average annual effective doses averaged 7 mSv, with 15% above 15 mSv [H6]. This information is supported by information from other parts of Australia [J1] and from Malaysia [O1], India [M4] and Brazil [C3], but more data are required from such producer countries for a full global assessment.

348. Similar difficulties affect the assessment of occupational exposures from the mining and processing of phosphate ores. Sedimentary phosphate may contain about 1,500 Bq kg^{-1} of uranium. Surface mining is followed by milling and other physical treatment to upgrade the ore, most of which is later digested with acid to produce fertilizers. The main mechanisms of exposure in the early stages are gamma-irradiation and the inhalation of radon progeny, with some inhalation of ore dust. Data for the initial stages in two mines in the Syrian Arab Republic [O5] indicate that exposures overall are unremarkable and that even the maximum values are not very high. The annual effective doses from gamma rays averaged 0.3 mSv in two mines and 0.1 mSv in two processing plants. The doses from radon progeny ranged from 0.1 WLM to a maximum of 0.7 WLM (i.e. about 0.6 mSv to about 4 mSv using a conversion factor of 5.6 mSv WLM^{-1}). The inhalation of dust could have added 0.5-1 mSv to these doses. Limited, but consistent data are available from India [L3], Israel [T1], United States [H9], Tunisia [M13] and Yugoslavia [K7]; more are needed for a better estimate of exposures worldwide.

349. Based on the limited data available for the mining and processing of mineral sands and phosphate ores, it is evident that the collective doses from these operations are small in comparison with those from underground mining. It is unlikely that the collective effective dose from such operations would exceed about 100 man Sv, although further data are needed to confirm such an estimate.

3. Transport, storage and use of phosphates

350. In the UNSCEAR 1988 Report [U1] very approximate estimates were made of the collective doses worldwide arising in the processing and transport of phosphate rocks and in the transport, storage and use of phosphates as fertilizers. Based on the extrapolation of limited experience in Germany, in which account was taken only of exposure by external irradiation, a worldwide annual dose of about 70 man Sv was attributed to these operations. No further data have been obtained that would allow updating this estimate, which remains very approximate.

B. AVIATION

1. Air travel

351. Flight altitude and duration are the principal determinants of cosmic-ray doses to airline crews and passengers. Modern commercial aircraft have optimum operating altitudes near 13 km, but flight paths are assigned according to use and safety requirements. There do not seem to be enough data available to determine average flight patterns [W2]. In the UNSCEAR 1988 Report [U1], a representative operating altitude of 8 km was assumed, because of the predominance of short-distance flights, with an average speed of 600 km h^{-1}. Other studies assume other altitudes and speeds: for example, an altitude of 9 km and a speed of 650 km h^{-1} were used for an assessment in the United Kingdom [H1], and an altitude of 7 km was used for flights by United States carriers lasting less than an hour and 11 km for longer flights [O4]. At 8 km the effective dose equivalent has been estimated to be 2 μSv h^{-1}, this being the sum of the absorbed dose in tissue of the directly and

indirectly ionizing radiations [H4, N5]. A worldwide measurement programme on Lufthansa airplanes indicated that most flight altitudes were in the range of 10 to 11.9 km with effective dose equivalent rates of less than 5 μSv h^{-1} and 8 μSv h^{-1}, respectively, at these altitudes [R7, R8].

352. Computational codes have been developed to calculate the radiation levels throughout the atmosphere (e.g. [O4]), and additional measurement experience is being acquired (e.g. [R8]). Preliminary assessments of cosmic-ray dose accounting for changes in quality factors [I7] are indicating that effective doses are likely to be a few tens of per cent greater than the effective dose equivalents reported above. Pending these revised estimates and given the other uncertainties inherent in the estimation of doses to aircrew, the simplifying assumption is made here that the effective doses are numerically equal to the reported effective dose equivalents. In addition to variations with altitude, the cosmic-ray dose changes with latitude and solar cycle modulation.

353. A limited number of supersonic airplanes operate commercially and cruise at about 15 km. Doses on board are routinely determined with monitoring equipment. Effective dose equivalent rates are generally around 10 μSv h^{-1}, with a maximum around 40 μSv h^{-1} [U1]. In two years from July 1987, the overall average on six French airplanes was 12 μSv h^{-1} with monthly values up to 18 μSv h^{-1} [P2]; in 1990, the average was 11 μSv h^{-1} and the annual dose to aircrew about 3 mSv [M5]. During 1990, the average dose rate for about 2,000 flights by British airplanes was 10 μSv h^{-1}, with a maximum value of 50 μSv h^{-1} [D4]; annual doses to aircrew are around 2.5 mSv on average with a maximum around 17 mSv [H1]. Neutrons contribute about half of the overall effective dose equivalents. The monitoring equipment serves to warn of solar flares so that the airplanes can be brought to lower altitudes. This is a very small sector of the commercial air transport industry.

354. In the UNSCEAR 1988 Report [U1] annual flying time of 600 hours was assumed to be representative for aircrew, which is compatible with experience in the United Kingdom [H1], Germany [R7, R8] and France [M5]; flying times may be 50% higher in the United States [F3]. The annual collective effective dose equivalent to aircrew in the United States was estimated to be about 400 man Sv in 1985, based on an average annual effective dose equivalent of 3.5 mSv to some 114,000 crew members (of which 46,000 and 68,000, respectively, were flight crew and cabin attendants) [E3]. The annual collective effective dose equivalent to Lufthansa aircrew in Germany has been estimated to be about 30 man Sv, based on 12,000 aircrew and average annual individual dose of 2.5 mSv [R7, R8]. Values reported for a number of other European carriers [M5, M6, S9] are consistent with an estimate of annual effective dose equivalents to aircrew of 2.5 mSv. An approximate estimate of the worldwide collective effective dose equivalent can be made by assuming an average annual dose of 3 mSv (i.e. intermediate between European and United States experience) and taking account of the number of aircrew worldwide which, in the late 1980s, was about a quarter of a million [I12]. The resulting estimate of the worldwide annual collective effective dose equivalent is about 800 man Sv. This value is several times higher than previously estimated [U1]. Although still only approximate, it is better substantiated and should be a more accurate estimate.

355. In addition to aircrew, some other persons, such as professional couriers, receive higher exposures in air travel. An analysis of passengers using London airport in 1988 showed that one in four had made 10 or more journeys during the previous year, corresponding to 30 or more hours aloft, but some professional couriers undertook 200 journeys a year, implying 1,200 flying hours [G2]. The number of these individuals is unknown, but it must be some small fraction of the number of aircrew.

2. Space travel

356. Space travel is restricted to a small number of astronauts and cosmonauts. Current space travel from the United States and the former USSR is restricted to low earth orbits at various inclinations [B13]. Doses are strongly dependent on altitude and less so on inclination. Experimental results from six shuttle missions [B13, N3] and seven space-station missions [B13, N4] indicated that daily effective dose equivalents at altitudes from 300 to 520 km were 0.1-0.7 mSv. Low- and high-LET radiations were determined separately; each contributed about half of the total. Because of the complexities of radiation fields in space vehicles, it is not easy to estimate exposure in terms of effective dose; the simple assumption is therefore made that it is numerically equal to the foregoing values. Because so few individuals are involved, the collective dose from this practice is quite low.

357. A comprehensive review of radiation in space has been published by NCRP [N3]. It treats in detail the physical and biological aspects of the subject and projects dose for possible future space missions.

C. OTHER OCCUPATIONS AND PRACTICES

358. In addition to mines, other places of underground work with potentially increased radon levels include natural caves, subway systems and power stations. In

Germany radon levels exceed 1,000 Bq m^{-3} in 40% of all such underground work locations; in 10%, they exceed 5,000 Bq m^{-3} [S10]. Radon levels in caves in the karstic or limestone regions of several countries are similar [H8, R4, S12]. Unlike mines, caves may not have efficient mechanical ventilation, so radon and progeny levels may be quite high. Typical concentrations of potential alpha energy are about 0.3 WL, implying about 5 mSv effective dose in three months or 20 mSv for a full working year (assuming a conversion factor of 5.6 mSv WLM^{-1}). Some caves exceed 2 WL, however, which could imply substantial doses for some guides.

359. In the UNSCEAR 1988 Report [U1] consideration was given to a number of other industrial processes and occupations that could lead to enhanced levels of exposure to natural sources of radiation. In general, the data for these practices and occupations were not sufficient to enable reliable estimates to be made of worldwide collective doses. Their contribution to the total worldwide occupational exposure from natural sources of radiation is, however, unlikely to be significant. Nonetheless, the collective dose to workers at coal-fired power plants was estimated. The main source of exposure in this case is thought to be the inhalation of airborne fly ash, which contains elevated levels of a number of naturally occurring radionuclides. The upper estimate of the worldwide annual collective effective dose was 60 man Sv, subject to the following assumptions: global annual production of electrical energy of 600 GW a; a labour force of 500 to produce 1 GW a per year; and an individual annual committed effective dose per worker of 0.15 mSv. The last value was estimated for the most exposed group of power station workers in the United Kingdom, assuming exposure to dust at concentrations of 0.5 mg m^{-3}; this value, if applied to all workers, gives an overestimate for the collective dose from the practice.

D. SUMMARY

360. A summary of average individual and collective effective doses to workers worldwide involved in occupations or practices that have increased exposures to natural sources of radiation are summarized in Table 39. The worldwide annual collective effective dose is estimated to be 8,600 man Sv. This dose arises mainly (about 90%) from underground mining. About 45% of the collective dose from mining arises from coal mining and about 55% from the mining of other materials. The estimated collective dose to aircrew is about 800 man Sv (about 10% of the total). The contribution from all other activities is small by comparison and appears unlikely to exceed a few hundred man sievert.

VII. ACCIDENTS

361. Accidents that occur in the course of work add to occupational exposures. Accidents with clinical consequences for those exposed that occurred in 1975-1989 are listed in Table 40, separated into accidents occurring in 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 on Occupational Exposures. Some additional entries have been made from other compilations of accidents [I11, R3] to the extent that dose information was available or clinical consequences could be ascertained. The accidental exposures listed are for those which have occurred in the course of work; accidental exposures from the theft or loss of industrial or medical sources have been excluded as have accidental exposures of patients during diagnosis or therapy.

362. The majority of accidents occurred in industrial uses of radiation, involving radiography sources and irradiation facilities. In most cases either human carelessness or malfunction of the equipment has been the cause. Two accidents resulted in high doses that caused deaths: one death at Brescia, Italy in 1975, and one in El Salvador in 1989. None of the accidents reported to workers involved in medical uses of radiation caused deaths.

363. There have been relatively few accidents involving serious radiation injury to workers in operations of the nuclear fuel cycle. On the other hand, the accident at Chernobyl in 1986 caused high exposures and acute radiation sickness in 237 persons and the deaths of 28 of them. These were workers at the reactor and members of the fire-fighting and emergency crew, who dealt with the accident in its initial stages. Two other workers at the reactor died as a result of the explosions and fire rather than of radiation injuries. An accident at a criticality facility at Buenos Aires in 1983 resulted in the death of one worker.

364. While accidents causing deaths are well known, there is likely to be substantial underreporting of other accidents. Two considerations support this premise. First, for the period 1975-1984, the number of accidents reported here is almost twice as great as the number reported by Rodrigues de Oliveira [R3], which was based on a detailed and comprehensive review of the literature; it would thus appear that many accidental exposures with actual or potential clinical consequences have not been reported in the literature. Secondly, the data reported in response to the UNSCEAR questionnaire are by no means comprehensive, either in terms of the countries reporting data or in the completeness of the data reported for the period of interest. As is apparent from Table 40, either there have been very large variations in the frequency of accidents in some countries in the different five-year periods, or, as is more likely, the reported data are incomplete. It is difficult to assess the extent of any underestimate, but a very rough extrapolation of the data provided in response to the UNSCEAR Survey on Occupational Exposures suggests that the number of accidents with potential or actual clinical consequences may have been two or three times as great as reported here. There is much uncertainty in this estimate, given the few countries reporting data.

365. It would be of interest to know the collective dose to workers caused by accidents, but the data are too incomplete to make other than a very rough estimate. The doses to those acutely exposed in the Chernobyl accident were reported in detail in the UNSCEAR 1988 Report [U1]. The collective dose to the 28 workers who died was 240 man Sv. The remainder of the workers accounted for 370 man Sv, estimated from the distribution of workers according to degree of radiation sickness and using the mid-point doses that characterize these degrees. The three deaths in other radiation accidents may be estimated to account for 30 man Sv. The remaining entries, even assigning up to 0.5 Sv per accident and underreporting by a factor of 2-3 could add at most about 200 man Sv; this is likely to be a major overestimate, because the majority of accidents involve skin or extremity exposures. This makes a total of less than 900 man Sv for all accidents occurring in 1975-1989. About two thirds of the total resulted from the Chernobyl accident, with the remainder adding at most about 15 man Sv per year to occupational radiation exposures; in reality the latter dose may be substantially less.

366. Additional occupational radiation exposure occurs in the aftermath of accidents, in clean-up and decontamination work. The Chernobyl accident alone involved 600,000 workers, many or possibly most of whom were exposed to the maximum permitted dose limit. This represents a very special case, but nevertheless a substantial collective dose. Only if accurate and more complete records are maintained of exposures caused by accidents can estimates of this component of occupational radiation exposures be improved.

367. In summary, the number of accidents to workers worldwide with clinical consequences reported here for the period 1975-1989 is about 90 involving 362 workers; because of underreporting, the actual number of accidents, may have been two or three times greater. The reported data are too incomplete to make any reliable estimate of trends in accidental exposures with time.

CONCLUSIONS

368. Occupational radiation exposures have been evaluated for five broad categories of work, namely the nuclear fuel cycle, defence activities, industrial uses of radiation (excluding the nuclear fuel cycle and defence), medical uses of radiation and occupations where enhanced exposures to natural sources of radiation may occur. Results for 1985-1989 are summarized in Table 41 and, in abbreviated form, for the whole period of interest (1975-1989) in Table 42. The contribution of each category to the overall levels of exposure and the trends with time are illustrated in Figure XXV. The worldwide average individual and collective effective doses have been derived largely from data reported in response to the UNSCEAR Survey of Occupational Exposures, supplemented where appropriate by data from the literature.

369. *Summary of exposures in the period 1985-1989.* The average number of monitored workers worldwide involved with man-made uses of radiation in the period 1985-1989 is estimated to be about 4 million. The majority (about 55%) of these are involved with medical uses of radiation, with about 22%, 14% and 10% with the commercial nuclear fuel cycle, industrial uses of radiation and defence activities, respectively. About 5 million workers are estimated to be exposed to natural sources of radiation at levels in excess of average background levels. By far the majority (about

75%) are coal miners; other occupational groups contributing significantly to this total are underground miners in non-coal mines (about 13%) and aircrew (about 5%).

370. The worldwide average annual collective effective dose to workers from man-made sources of radiation in 1985-1989 is estimated to be about 4,300 man Sv. The collective effective dose from exposures to natural sources (in excess of average levels of natural background) is estimated to be about 8,600 man Sv; it arises mainly from underground mining (about 90%), with broadly comparable contributions from coal mining and the mining of other materials (other than uranium). The estimated collective dose from natural sources of radiation is, however, associated with much greater uncertainty than that from man-made sources of radiation.

371. Of the annual collective effective dose from exposure to man-made sources of radiation (4,300 man Sv), about 58% arises from operations in the nuclear fuel cycle (2,500 man Sv), about 23% from medical uses (1,000 man Sv), about 12% from industrial uses of radiation (510 man Sv) and about 6% from defence activities (250 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 reading, which is generally entered directly into dose records, may overestimate the effective dose by a large factor.

372. The average annual effective dose to monitored workers varies widely between occupations and also between countries for the same occupation. The worldwide average annual effective doses to monitored workers in industry (excluding the nuclear fuel cycle), medicine and defence activities are less than 1 mSv (about 0.9 mSv, 0.5 mSv and 0.7 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 those in other occupations; for the fuel cycle overall, the average annual effective dose is about 2.9 mSv. For the mining of uranium the average annual effective dose to monitored workers in countries reporting data was about 4 mSv, and for uranium milling operations it was about 6 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 2 mSv, with doses about 50% greater, on average, in HWRs and smaller by a factor of about 2, on average, in GCRs. The individual doses in fuel reprocessing are comparable with those in reactors, whereas those in fuel enrichment are much smaller.

373. The percentage of monitored workers worldwide involved with the use of man-made sources of radiation receiving annual effective doses in excess of 15 mSv is estimated, on average, to have been about 3% during the period 1985-1989. There is, however, considerable variation in this value between occupations. Typically, about 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 10% of monitored workers, on average, exceeded this level of annual effective dose. There is, however, considerable variation between different stages of the fuel cycle (i.e. about 20% for uranium mining and milling, about 3% averaged over all reactors but varying within a range of essentially zero to about 7% depending on the reactor type, about 6% for reprocessing, on average, about 0.2% for fuel fabrication and essentially zero for enrichment). It should be noted that the above percentages, where they include a contribution from workers in uranium mining and milling, may be overestimates. This is due to the assumption that the reported distribution ratios for uranium mining and milling are applicable to an effective dose of 15 mSv; strictly they apply to a dose less than 15 mSv because of the change in the conversion factor (compared with that used in the reported data) for exposures to radon progeny adopted in this Annex.

374. 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) which arises from annual individual doses in excess of 15 mSv is estimated to have been about 30% to 40% during the period 1985-1989. There is, however, considerable variation in this value between occupations. Typically, about 25% and 30%, respectively, of the collective dose in medicine and industry (excluding the nuclear fuel cycle and defence) are estimated to have arisen from annual individual doses in excess of this level. For the nuclear fuel cycle as a whole, about 40% 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 (i.e. about 50% for uranium mining and milling, about 35% averaged over all reactors but varying within a range of essentially zero to about 50% depending on the reactor type, about 10% for oxide fuel reprocessing, about 2% for fuel fabrication and essentially zero for enrichment). It should be noted that the above percentages, where they include a contribution from

workers in uranium mining and milling, may be overestimates for the reasons set out above.

375. The average annual effective dose to workers exposed to enhanced levels from natural sources of radiation, 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 1 mSv. In other (non-uranium) mines the worldwide average effective dose is estimated to be about 6 mSv. Aircrew are estimated to receive an average annual effective dose of about 3 mSv.

376. ***Trends in exposures over the period 1975-1989.*** Trends in exposure from man-made sources are illustrated in Figure XXV for each of the main occupational categories considered in this Annex. The trends in occupational exposures from natural sources have not been quantified because insufficient data are available to make meaningful estimates; the few data that do exist, however, suggest that exposures (excluding those to aircrew) before the second half of the 1980s were greater than those estimated here, possibly much greater. The latter is due to somewhat less attention being given in the past to control and reduction of exposures in underground mining.

377. The worldwide annual average number of workers involved with man-made uses of radiation is estimated to have increased from about 2.5 to about 4 million between the first and third five-year periods. The greatest increase (from about 1.3 to about 2.2 million) has been in the number of monitored workers in medicine. The number of monitored workers in the nuclear fuel cycle has also increased significantly (by about 50% from about 0.6 to about 0.9 million). Increases in the numbers of the monitored workers in defence activities and other industrial uses of radiation have been modest by comparison.

378. The annual collective effective dose, averaged over five-year periods, for all operations in the nuclear fuel cycle changed little over the period 1975-1989, notwithstanding the large increase (three to fourfold) in electrical energy generated by nuclear means; some changes, however, occurred in particular stages of the fuel cycle. The annual average collective dose from uranium mining increased by about 25% between the first and second five-year periods decreasing again to about its former level in the third period. There was a decrease by a factor of almost 2 for fuel fabrication, reprocessing and research. The collective dose from reactors increased over the period by a factor approaching 2, with almost all of the increase occurring during 1975-1979 and 1980-1985. The increase in dose between the first two five-year periods was largely attributable to the major plant safety modifications carried out in the earlier 1980s in response the accident at Three Mile Island. Indeed, but for the accident at Chernobyl, the annual average collective dose from reactors in 1985-1989 would probably have decreased relative to the preceding five-year period. Average annual individual effective doses to monitored workers in nuclear fuel cycle operations typically decreased by a factor of about 2 in most stages of the fuel cycle between 1975-1979 and 1985-1989; for uranium mining, the decrease with time was only about 20%.

379. 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, the normalized collective dose has decreased by almost a factor of 2 from about 20 man Sv $(GW\ a)^{-1}$ to about 12 man Sv $(GW\ a)^{-1}$, with most of this decrease occurring between the second and third five-year periods. For reactors, between the first and second five-year periods, the normalized collective doses changed little, but large decreases occurred in the third period; decreases by a factor of about 2 occurred for PWRs, BWRs and HWRs. These decreases in the third period were a consequence of the completion of most of the safety modifications made following the accident at the Three Mile Island reactor and the much greater attention paid by utilities and regulators to the reduction of occupational exposures in both existing and new reactors. Substantial reductions (by about an order of magnitude) occurred in the normalized collective dose for the fabrication of LWR fuel, although these doses may be underestimates because they do not take account of internal exposures. The normalized doses for the fabrication of other fuels did not decrease. Indeed, those for GCRs would appear to have increased with time; much of this increase, however, is more apparent than real, due to the fact that internal exposures were included only for the third period. For uranium mining, the normalized collective dose decreased by about 25% over the period analysed. The normalized dose for reprocessing oxide fuels changed little over the period analysed, whereas that for Magnox fuels decreased by about a third.

380. 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. It decreased, however, by a factor of almost 2 in the second half of the 1980s. This same trend is reflected in estimates of individual dose; the annual effective dose to monitored workers decreased from an average of about 1.5 mSv, over the period 1975-1984, to an average of about 0.9 mSv in the second half of the 1980s. In defence activities both the average individual and collective doses decreased by a factor of nearly

2 over the period analysed. These decreases were largely a consequence of reductions in doses achieved in the operation and maintenance of nuclear navies, notwithstanding the increase both in the number of ships in operation and in those undergoing refit over this time.

381. The worldwide average annual collective effective dose from all medical uses of radiation, about 1,000 man Sv, changed little over the three five-year periods. A clear downward trend is, however, evident in the worldwide average annual effective dose to monitored workers, which decreased from about 0.8 mSv in the first five-year period to about 0.5 mSv in the third; there was, however, considerable variation between countries. The annual average number of monitored workers in medicine increased by about 75% over the three periods, and this is the reason why 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.

382. The percentage of monitored workers worldwide involved with all uses of man-made sources of radiation receiving annual effective doses in excess of 15 mSv has decreased progressively from an average of about 5% to about 3% between the first and third five-year periods. This same downward trend is evident in the percentages of nuclear fuel cycle and medical workers worldwide receiving annual doses in excess of this same level. The tabulated data for medical workers show an increase in the third period. This increase, however, is more apparent than real and is due to the inclusion in this period only of data for one country with a very high value of this fraction; if this country were excluded, the trend would be downwards for medical workers throughout the period (see Section V.E). For industrial workers (excluding the nuclear fuel cycle and defence) worldwide there is little evidence in support of any clear trend in the percentage of workers receiving annual doses in excess of 15 mSv.

383. 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 has also decreased progressively from about 45% to about 36%, on average, between the first and third five-year periods. 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.

384. *Cumulative exposures.* Cumulative or lifetime exposures of workers have been analysed to only a limited extent. The examination of termination records has given average rates of dose accumulation for various career lengths, but there was no assurance that the records were either complete or accurate. Some indications of lifetime exposures may be provided by estimates of average annual exposures and career lifetimes, but both parameters are extremely variable between individuals within particular occupations, as well as between occupations and from one country to another. To evaluate actual experience, the need exists for more complete records of employment at all locations and complete dosimetry, including external and internal exposures. Improved data on this aspect can be expected in the next few years with the increasing use of computerized databases for occupational exposures and the compilation of data suitable for epidemiological studies on workers.

385. *Accidental exposures.* 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 uses of radiation and that most of them involved industrial radiography sources. By far the majority of accidental exposures of sufficient magnitude to cause clinical effects were associated with localized exposures to the skin or hands. From 1975 to 1989, 31 people died as a result of radiation exposures received in accidents; 28 of these were at Chernobyl. The number of accidents to workers worldwide with actual clinical consequences that has been reported in the period 1975-1989 is about 90. Because of underreporting of non-fatal accidents, the actual number may have been two or three times greater.

386. *Comparison with previous estimates of occupational exposures.* 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 have been reflected in the responses to the UNSCEAR Survey and have led to improved estimates of occupational exposures. The current estimate of the annual collective effective dose during the second half of the 1980s from occupational exposures to man-made sources of radiation (4,300 man Sv) is lower by a factor of 2 than the estimate made by the Committee in the UNSCEAR 1988 Report for the first half of the 1980s [U1]; the current analysis, however,

suggests that the latter was an overestimate by about a factor of 2 and that the actual reduction in collective dose over this period was relatively small, about 15%-20%.

387. The largest change in the estimates of annual collective dose is for medical uses of radiation. The current estimate indicates that the annual collective dose has remained relatively unchanged over the whole period analysed at about 1,000 man Sv. This is lower by a factor of 5 compared with the estimate made in the UNSCEAR 1988 Report [U1] for the first half of the 1980s, indicating that the latter was overestimated by a large factor; moreover, as has been noted, the current estimate may still be too large by a factor of 2 or more. The annual collective dose from industrial uses of radiation (excluding the nuclear fuel cycle and defence) is estimated in this analysis to have decreased by about a factor of 2 (from about 900 to 500 man Sv) between the first and second halves of the 1980s. The current estimate of the collective dose for the first half of the 1980s is about a factor of 2 lower than that estimated previously in the UNSCEAR 1988 Report [U1], based on data available at that time.

388. For the nuclear fuel cycle the greatest changes, compared with earlier estimates, are for the mining and milling of uranium and reactor operation. The present estimate of the normalized collective dose during the second half of the 1980s from mining and milling of uranium [about 4.8 man Sv $(GW\ a)^{-1}$] is about seven times greater than estimated previously [U1]. This previous estimate would, however, appear to have been an underestimate by an even greater factor. The current analysis indicates that the normalized collective dose in the early 1980s was actually about 20% greater than that for the second half of the 1980s. The present estimate of the normalized collective dose from reactor operation [about 5.8 man Sv $(GW\ a)^{-1}$] for the second half of the 1980s is smaller, by a factor of about 2, than estimated previously [U1] for the first half of the 1980s; this change reflects a real reduction in dose between the first and second halves of the 1980s, due largely to the completion of plant modifications to LWRs following the accident at Three Mile Island and, to a lesser extent, to the commissioning of new reactors in several countries.

389. The present estimate of the collective effective dose from exposures to enhanced natural sources of radiation at work is about two to three times smaller than the estimate made by the Committee in the UNSCEAR 1988 Report [U1]. Significant differences are apparent, however, in the respective estimates depending on the occupation. For coal mining and aircrew, the present estimates are factors of about 2 and 4 times greater, respectively, than those made previously; the present estimate for other mining (excluding uranium) is, however, a factor of about 5 times smaller than that made previously. The estimates of exposures to natural sources of radiation are not, however, as well supported by data as those for man-made sources. Further monitoring and investigation are needed of this important component of occupational exposures.

Table 1
Occupational categories used by UNSCEAR for evaluating exposures

Exposure source	*Occupational categories*
Nuclear fuel cycle	Uranium mining and milling Uranium enrichment and conversion Fuel fabrication Reactor operation PWRs, BWRs, HWRs, GCRs, LWGRs, FBRs Fuel reprocessing Research and development [a]
Defence activities	Nuclear weapons production Naval nuclear propulsion Other [b]
Industrial uses of radiation (excluding the nuclear fuel cycle and defence activities)	All industrial uses Industrial radiography Fixed, mobile Luminizing Radioisotope production and distribution Well logging Accelerator operation [c] Tertiary education and research [d] Other [e]
Medical uses of radiation	All medical uses Diagnostic radiography Dental radiography Nuclear medicine Radiotherapy Veterinary practice
Natural sources	Underground mining coal other (excluding uranium) Surface mining Aircrew Other

[a] Limited, in principle, to activities directly attributed to the commercial nuclear fuel cycle. It is recognized, however, that because of the way data are collected, the data attributed to this category may include exposures arising from other activities.

[b] To include all other uses encountered in civilian occupations (e.g. non-destructive testing, transport, research, education, etc.)

[c] Limited to accelerators used for nuclear physics research at universities and national or international laboratories.

[d] Limited to tertiary educational establishments (e.g. universities, polytechnics, research institutes with an important educational role, etc.).

[e] The sum of all other industrial uses of radiation (e.g. industrial irradiation facilities, etc.). The exposures attributed to this category should be equal to that for all industrial exposures less the sum of the exposures for those uses separately reported.

Table 2
Dose monitoring and recording procedures for occupational exposures in industry
Data from UNSCEAR Survey of Occupational Exposures unless otherwise indicated

Country	*Occupation*	*Monitored workforce*	*Minimum detectable level (MDL) or recording level*	*Dose recorded when less than MDL*	*Dose recorded for lost dosimeters*	*Doses to contractors included*	*Corrections made to avoid multiple entries for the same individual*
Argentina	All	Those in controlled areas	0.1 mSv	0	Mean value of previous 3 months	Yes	No
Australia	All	Those using radiation devices	0.01 mSv (x) 0.07 mSv (γ)	0	0		Yes
Canada [a]	Mining and milling Reactor operation Other		0.01 WLM 0.01-0.2 mSv 0.2 mSv	0 0 0	No fixed policy No fixed policy No fixed policy	Yes Yes Yes	Yes Yes Yes
Chile	All	Category A workers	0.05 mSv	0.05 mSv	Mean value of periods without accident		
China (Taiwan Province)	Reactor operation All other		0.003-0.05 mSv	Reading 0	Pocket dosimeter or average dose 0	Yes	No
Czechoslovakia	Reactor operation Other	Those wearing personal dosimeters	0.1 mSv 0.2 mSv	0 [b] 0	Mean value for previous 12 months Mean value for previous 12 months	No No	No No
Denmark	All		0.1 mSv	0	0	Yes	Yes
Finland [c]	Reactor operation Other	Those who may exceed 1/3 of dose limit plus optional users	0.1 mSv 0.1 mSv	0 0	Estimate based on working conditions 0	Yes Yes	No No
France	Reactor operation Reprocessing Uranium mining Research	Those provided with a personal dosimeter	0.01 mSv 0.15 mSv 0.20 mSv	0.1 mSv 0 Various 0	Based on electronic dosimeter reading Dose reconstruction after enquiry Attributed by local RP officer Attributed by local RP officer	Yes [d] Yes Yes Yes	No No No No
German Dem. Rep.	Mining (other than uranium)	Those in regions where alpha energy concentrations exceed 0.64 μJ/m^3	approx. 2 μSv		Attributed by controlling authority	Yes	Not necessary
Germany, Fed. Rep.	Reactor operation Other	As defined by Radiation Protection Ordinance Those in controlled areas	1 μSv (GM) 0.1 mSv (film) 0.1 mSv (>1978) 0.4 mSv (<1979)	 0 0	Redundant system used; if both lost estimate based on working conditions	Yes Yes	No No
Hungary [e]	All	Those who may exceed 1/10 of dose limit	0.1 mSv [d]	0	0	Yes	Not necessary
India			0.05 mSv (x) 0.1 mSv (n,γ)	0	Mean value of previous 12 months	Yes [f]	Yes
Indonesia	All		0.05 mSv	0.05 mSv		Yes	Yes

Table 2 (continued)

Country	*Occupation*	*Monitored workforce*	*Minimum detectable level (MDL) or recording level*	*Dose recorded when less than MDL*	*Dose recorded for lost dosimeters*	*Doses to contractors included*	*Corrections made to avoid multiple entries for the same individual*
Ireland	All		0.2 mSv (<1987) 0.15 mSv (>1987)	0	0	Yes	No (not significant)
Italy	All		0.1 mSv	0	Mean value for remainder of year		
Japan	Reactor operation Other	Those in controlled areas Those in controlled areas	0.1 mSv 0.1 mSv (TLD) 0.2 mSv (film)	0	Maximum individual dose in group	Yes	No
Netherlands	Accelerators		0.01 mSv	0	0	Yes	
Norway	All		0.4 mSv	0	0	Yes	No
Portugal	All		0.2 mSv				
Republic of Korea	Fuel fabrication Reactor operation Research		0.05 mSv 0.001 mSv 0.1 mSv	0.05 mSv 0 0.095 mSv	Pocket dosimeter or average dose Pocket dosimeter or work condition 30 mSv per quarter	Yes Yes No	Yes Yes No
Spain	Reactor operation Mining and fuel fabrication Other		0.1 mSv 0.2 mSv 0.05 mSv	0 0 0	Area or other dosimeter or 4 mSv Area or other dosimeter or 4 mSv Area or other dosimeter or 4 mSv	Yes Yes Yes	No No No
South Africa	Reactor operation Other		0.1 mSv 0.2 mSv	0 0	Based on QFD reading 4 mSv	Yes Yes	Yes No
Sweden	All		0	0.1 mSv	0	No	No
USSR			0.1 mSv	0.1 mSv			
United Kingdom	BNFL sites Weapons	Those in controlled areas	0.1 mSv 0.05 mSv (external) 0.01 mSv (internal)	As assessed 0 [g]	Working conditions or dose limit rate 4.15 mSv	Yes [h] No	Not necessary Partially
United States	USNRC licensees		0.01 mSv	0	Estimated by licensee	Yes	No

[a] A change from film to TLD dosimetry took place over a five-year period from 1977 to 1981 without any significant change observed in the statistics.
[b] Average individual and collective doses estimated from log-normal fits to data and therefore account is taken of doses occurring below MDL and recorded as zero.
[c] The database includes only workers who have exceeded the recording level, which for reactors was 0.1 mSv with dosimeters issued monthly and 0.5 mSv for all other industrial occupations with dosimeters issued quarterly; the latter recording level was reduced to 0.3 mSv in 1989. Before 1990 the database does not contain the numbers of monitored workers.
[d] Only in collective dose estimates.
[e] Doses recorded above the recording level, which is 0.1 mSv per month for reactor workers and 0.2 mSv per two months for workers elsewhere.
[f] For three out of four power stations.
[g] Before 1986 the dose recorded when less than MDL was 0.05 mSv (external) and 0.01 mSv (internal).
[h] In the BNFL (British Nuclear Fuels plc.) data presented in this Annex, contractors are included only for reprocessing operations.

Table 3
Exposures from uranium mining [a]
Data from UNSCEAR Survey of Occupational Exposures unless otherwise indicated

Country and period	Annual amount of uranium mined [c] (kt)	Equivalent amount of energy [d] (GW a)	Monitored workers (thousands)	Measurably exposed workers (thousands)	Annual collective effective dose [b]			Average annual effective dose		Contribution of exposure pathway (%)			Distribution ratio	
					Total (man Sv)	Average per unit uranium extracted (man Sv per kt)	Average per unit energy generated [man Sv (GW a)$^{-1}$]	Per monitored worker (mSv)	Per measurably exposed worker (mSv)	External	Radon daughters	Ore dust	NR_E [e]	SR_E [e]
Underground mines														
Argentina [f] 1975-1979	0.041	0.19	0.25		4.59	111	24.5	18.0					0.54	0.95
Australia [g] 1988-1989			0.41	0.41	1.63			3.98	3.98	39	25	36	0.061	0.22
Bulgaria [I10] 1985-1989			0.50		23.1			46.1		0	100	0		
Canada [h, i] 1975-1979	4.73	21.5	5.78	5.06	40.2	8.51	1.87	6.96	7.95	37	63	0.25	0.20	0.57
1980-1984	5.97	27.1	8.06	6.90	49.6	8.30	1.83	6.15	7.18	43	57	0.30	0.23	0.62
1985-1989	5.10	23.0	5.19	4.36	30.2	5.59	1.23	5.82	6.93	40	60	0.26	0.26	0.67
China [I10] 1985-1989			6.6		114			17.3		35	65	0		
Czechoslovakia [j]														
1975-1979	1.78	8.11	9.06		60.4	33.9	7.45	6.67		14	86	0		
1980-1984	2.02	9.19	8.48		50.2	24.8	5.47	5.92		20	80	0	0.16	0.35
1985-1989	1.96	8.93	7.46		36.9	18.8	4.14	4.95		16	84	0	0.12	0.28
France [k] 1983-1984	1.85	8.42	1.28	1.25	17.0	9.18	2.02	13.3	13.6	28	72	0	0.48	
1985-1989	2.29	10.4	1.34	1.28	12.4	5.39	1.19	9.22	9.67	29	71	0	0.40	
Gabon [I10] 1985-1989			0.24		5.06			21.0						
German Dem. Rep. [l]														
1975-1979	6.26	28.5	14.7	14.7	160	25.5	5.61	10.9	10.9	29	57	14	0.46	0.72
1980-1984	4.73	21.5	15.1	15.1	147	31.0	6.82	9.69	9.69	29	57	14	0.42	0.65
1985-1989	4.07	18.5	16.1	16.1	133	32.7	7.18	8.24	8.24	29	56	15	0.31	0.57
India [m] 1981-1984	0.13	0.58	1.16		13.8	108	23.7	11.9		24	76	0		
1985-1989	0.15	0.68	1.35		15.2	101	22.3	11.3		23	77	0		
South Africa [n] 1975-1979	3.27	14.9	79.0		347	107	23.3	4.39		23	75	0		
1980-1984	5.07	23.0	93.6		399	78.8	17.3	4.27		25	75	0		
1985-1989	3.53	16.0	82.2		278	78.8	17.3	3.38		25	75	0		
USSR [I10] 1985-1989								16.3						

Table 3 (continued)

Country and period	Annual amount of uranium mined [c] (kt)	Equivalent amount of energy [d] (GW a)	Monitored workers (thousands)	Measurably exposed workers (thousands)	Annual collective effective dose [b] Total (man Sv)	Annual collective effective dose [b] Average per unit uranium extracted (man Sv per kt)	Annual collective effective dose [b] Average per unit energy generated [man Sv (GW a)$^{-1}$]	Average annual effective dose Per monitored worker (mSv)	Average annual effective dose Per measurably exposed worker (mSv)	Contribution of exposure pathway (%) External	Contribution of exposure pathway (%) Radon daughters	Contribution of exposure pathway (%) Ore dust	Distribution ratio NR_E [e]	Distribution ratio SR_E [e]
United States [o] 1975-1979	5.51	25.1	6.85		30.9	5.60	1.23	4.51			100			
1980-1984	5.01	22.8	5.89	3.83	19.4	3.86	0.85	3.29	5.05		100			
1985-1989	2.27	10.3	0.77	0.62	2.68	1.18	0.26	3.46	4.33		100			
Total of reported data [p]														
1975-1979	21.6	98.2	116		642	29.7	6.54	5.56		26	70	3.8	0.39	0.69
1980-1984	23.7	107	133		683	28.9	6.36	5.15		27	70	3.2	0.33	0.61
1985-1989	19.7	89.4	114		507	25.7	5.66	4.44		28	69	3.2	0.26	0.53
World [q] 1975-1979	45	200	240		1330	29.8	6.55	5.54		26	70	3.8		
1980-1984	55	250	310		1580	29.0	6.37	5.15		27	70	3.2		
1985-1989	44	200	260		1140	25.9	5.69	4.45		28	69	3.2		
Open-pit mines														
Argentina 1976-1979	0.067	0.302	0.122		0.302	4.54	1.0	2.48		82	18	0	0	0
1980-1984	0.146	0.664	0.954		2.29	15.7	3.45	2.40		84	17	0	0	0
1985-1989	0.092	0.418	0.509		1.25	13.5	2.98	2.45		82	18	0	0	0
Australia [g] 1988-1989	6.5	29.5	0.047	0.047	0.251	0.039	0.008	5.33	5.33	22	2.2	76	0	0
Canada [k,r] 1978-1979	2.09	9.50	0.444	0.406	0.996	0.476	0.105	2.24	2.46	13	84	2.7	0.008	0.037
1980-1984	2.28	10.4	0.820	0.520	0.751	0.329	0.072	0.92	1.44	46	47	6.5	0.001	0.021
1985-1989	6.71	30.5	1.09	0.876	1.16	0.152	0.034	1.07	1.32	35	39	5.6	0.001	0.010
China [I10] 1985-1989			0.78		1.49			1.91		52	48	0		
France [s] 1985-1989	0.7	3.18	0.41	0.41	0.862	1.23	0.271	2.09	2.09				0.005	
Spain [t] 1986-1989	0.360	1.64	0.375	0.226	0.257	0.712	0.157	0.684	1.14	100	0	0		
Total of reported data [u]														
1975-1979	1.11	5.05	0.34		0.827	0..744	0.164	2.40		29	69	2.1	0.0049	0.026
1980-1984	2.43	11.0	1.77		3.06	1.26	0.277	1.73		74	24	1.6	0.0003	0.006
1985-1989	10.3	46.8	1.62		2.53	0.246	0.054	1.57		60	34	6.2	0.0004	0.006
World [q] 1975-1979	7.1	32	3.9		7.76	1.09	0.239	2.01		29	69	2.1		
1980-1984	9.1	41	8.1		14.5	1.59	0.349	1.79		74	24	1.6		
1985-1989	14	62	2.5		3.76	0.258	0.057	1.56		60	34	6.2		

Table 3 (continued)

Country and period		Annual amount of uranium mined [c] (kt)	Equivalent amount of energy [d] (GW a)	Monitored workers (thousands)	Measurably exposed workers (thousands)	Annual collective effective dose [b]			Average annual effective dose		Contribution of exposure pathway (%)			Distribution ratio	
						Total (man Sv)	Average per unit uranium extracted (man Sv per kt)	Average per unit energy generated [man Sv (GW a)$^{-1}$]	Per monitored worker (mSv)	Per measurably exposed worker (mSv)	External	Radon daughters	Ore dust	NR_E [e]	SR_E [e]
Total uranium mining															
World	1975-1979	52	240	240		1300	26	5.7	5.5		26	70	3.8	0.37	0.69
	1980-1984	64	290	310		1600	23	5.5	5.1		27	69	3.1	0.30	0.61
	1985-1989	59	270	260		1100	20	4.3	4.4		28	69	3.2	0.25	0.52

[a] The data are annual values averaged over the indicated periods.

[b] Doses from inhalation of radon daughters estimated using a conversion factor of 5.6 mSv WLM^{-1}; this necessitated a revision of most of the data actually reported which were, in general, based on a conversion factor of 10 mSv WLM^{-1}.

[c] Uranium production data are those reported in response to the questionnaire. If nothing was reported, data were taken from [O2].

[d] Estimated on the simplifying assumption that all the mined uranium is used in LWRs. The assumed fuel cycle requirement is 220 t uranium per GW a.

[e] The values of NR and SR are those reported for the monitored workforce for E = 15 mSv, where the component of dose from radon progeny was derived assuming a conversion factor of 10 mSv WLM^{-1}. Because the radon doses have been modified here using a conversion factor of 5.6 mSv WLM^{-1}, the value of E to which the distribution ratios refer will be less than 15 mSv, the exact value varying with the country and period of interest (i.e. depending on the relative contribution of radon progeny to the total dose).

[f] Estimated by subtracting of reported data on open-pit mining from reported data for total mining; underground mining ceased after 1979.

[g] Data reported for exposed workers,which have been assumed to be the same as monitored workers.

[h] For 1975-1983 the reported data contain a contribution from milling.

[i] 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.

[j] Exposures from inhalation of dust are not included; measurements have indicated that it would contribute less than 3 mSv to the annual commited effective dose.

[k] The contribution indicated for radon daughters includes the contribution from inhalation of radon daughters and inhalation of dust; in 1989 the contribution of each of these components was comparable [P3].

[l] Doses estimated on basis of grab samples.

[m] The contribution from the dust is very small because of the low grade of the ore and has been ignored.

[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] Reported data only include exposures from inhalation of radon daughters.

[p] Tabulated data on uranium mined, number of workers, doses and distribution ratios comprise the sum or averages of data for Argentina, Canada, Czechoslovakia, France, the German Democratic Republic, India, South Africa and the United States (i.e. those countries for which data for at least one period are complete in terms of these quantities); the percentage contributions to exposure pathways are averaged over Australia, Canada, China, Czechoslovakia, the German Democratic Republic, France, India and South Africa, countries for which data are reported on all three contributions. 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.

[q] Estimates extrapolated from total of reported data, based on total uranium mined worldwide relative to that mined in reporting countries.

[r] Reported data before 1981 did not include external radiation; an external dose of 0.3 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.

[s] Normalized collective dose and number of workers from [P3] as approximate average of French open-pit mines in 1989; total collective dose and individual doses derived here using estimate of amount mined by subtracting that reported for underground mining from total mined given in [O2]. The percentage contributions of each exposure pathway are approximate averages for open-pit mines in France.

[t] Includes only external exposure; contribution from internal exposure judged negligible by comparison.

[u] Tabulated data on uranium mined, number of workers, doses and distribution ratios comprise the sum or averages of data for Argentina, Australia and Canada (i.e. those countries for which data for at least one period are complete in terms of these quantities); the percentage contributions to exposure pathways are averaged over Argentina, Australia Canada and China, countries for which data are reported on all three contributions. 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.

Table 4
Exposures from uranium milling and extraction [a]
Data from UNSCEAR Survey of Occupational Exposures unless otherwise indicated

Country and period	Annual amount of uranium milled [c] (kt)	Equivalent amount of energy [d] (GW a)	Monitored workers (thousands)	Measurably exposed workers (thousands)	Annual collective effective dose [b]			Average annual effective dose		Contribution of exposure pathway (%)			Distribution ratio	
					Total (man Sv)	Average per unit uranium extracted (man Sv per kt)	Average per unit energy generated [man Sv (GW a)$^{-1}$]	Per monitored worker (mSv)	Per measurably exposed worker (mSv)	External	Radon daughters	Ore dust	NR_E [e]	SR_E [e]
Australia [f]														
1988-1989	4.20	19.1	0.608	0.608	2.04	0.486	0.107	3.36	3.36	16	0.6	83	0	0
Canada [g]														
1975-1979	4.31	19.6	0.668	0.458	0.66	0.153	0.034	0.99	1.44				0.014	0.16
1980-1984	5.50	25.0	0.852	0.356	0.37	0.067	0.015	0.43	1.04	46	53	1.5	0.002	0.064
1985-1989	9.29	42.2	0.833	0.666	1.30	0.140	0.031	1.56	1.95	65	34	1.3	0.008	0.080
China [I10]														
1985-1989			3.05		9.67			3.17		16	43	42		
Czechoslovakia [h]														
1980-1984	1.82	8.27	1.13		11.4	6.28	1.38	10.1		6	14	80		
1985-1989	1.81	8.24	1.19		11.6	6.42	1.41	9.74		6	21	73		
France [i] [R1]														
1988-1989	2.77	12.6	0.34	0.33	2.04	0.737	0.162	5.93	6.28	29	71	0	0.08	
German Dem. Rep. [j]														
1975-1979	5.47	24.9	3.45	3.45	43.8	8.00	1.76	12.7	12.7	14	46	40	0.48	0.78
1980-1984	4.60	20.9	3.24	3.24	34.1	7.40	1.63	10.5	10.5	14	45	41	0.37	0.65
1985-1989	4.07	18.5	2.99	2.99	24.8	6.10	1.34	8.30	8.30	14	46	40	0.25	0.44
India [k]														
1981-1984	0.128	0.58	0.49		3.58	27.9	6.15	7.35		49	51	0		
1985-1989	0.150	0.68	0.58		3.40	22.6	4.97	5.86		49	51	0		
South Africa [l]														
1979	3.60	16.4	0.388	0.085	0.07	0.018	0.004	0.17	0.78	100	0	0		
1980-1984	4.46	20.3	0.648	0.277	1.93	0.432	0.095	2.97	6.95	100	0	0		
1985-1989	3.00	13.7	0.643	0.257	1.08	0.360	0.079	1.68	4.20	100	0	0		
United States [m]														
1975-1979	8.90	40.5	0.30	0.1	0.03	0.004	0.001	0.11	0.34	100	0	0		
1980-1984	16.8	76.4	4.80	3.0	4.48	0.267	0.059	0.93	1.49	100	0	0		
1985-1989	4.30	19.6	1.00	0.6	0.95	0.221	0.049	0.95	1.59	100	0	0		

Table 4 (continued)

Country and period	Annual amount of uranium milled [c] (kt)	Equivalent amount of energy [d] (GW a)	Monitored workers (thousands)	Measurably exposed workers (thousands)	Annual collective effective dose [b]			Average annual effective dose		Contribution of exposure pathway (%)			Distribution ratio	
					Total (man Sv)	Average per unit uranium extracted (man Sv per kt)	Average per unit energy generated [man Sv (GW a)$^{-1}$]	Per monitored worker (mSv)	Per measurably exposed worker (mSv)	External	Radon daughters	Ore dust	NR_E [e]	SR_E [e]
Total of reported data [a]														
1975-1979	18.7	84.9	4.41		44.5	2.38	0.52	10.1		14	46	40	0.41	0.76
1980-1984	28.8	131	10.4		53.2	1.85	0.41	5.1		15	39	46	0.30	0.64
1985-1989	22.4	102	6.98		43.7	1.95	0.43	6.3		16	37	47	0.18	0.43
World [o]														
1975-1979	53	240	12		124	2.36	0.52	10.0		14	46	40		
1980-1984	64	290	23		117	1.84	0.41	5.1		15	39	46		
1985-1989	58	260	18		116	2.01	0.44	6.3		16	37	47		

[a] The data are annual values averaged over the indicated periods.

[b] Doses from inhalation of radon daughters estimated using a conversion factor of 5.6 mSv WLM^{-1}; this necessitated a revision of most of the data actually reported which were, in general, based on a conversion factor of 10 mSv WLM^{-1}.

[c] Amounts of uranium milled are those reported in response to the questionnaire. If nothing was reported, data were assumed to be the amounts mined in the corresponding period [O2].

[d] 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)$^{-1}$.

[e] The values of NR and SR are those reported for the monitored workforce for E = 15 mSv, where the component of dose from radon progeny was derived assuming a conversion factor of 10 mSv WLM^{-1}. Because the radon doses have been modified here using a conversion factor of 5.6 mSv WLM^{-1}, the value of E to which the distribution ratios refer will be less than 15 mSv, the exact value varying with the country and period of interest (i.e. depending on the relative contribution of radon progeny to the total dose).

[f] Data reported for exposed workers, which have been assumed here to be the same as monitored workers.

[g] For 1975-1983, the quoted values are for extraction only; data for milling for this period are reported together with the mining data.

[h] Contribution from internal exposure is small and has not been explicitly estimated.

[i] The contribution from radon also includes the contribution from inhalation of ore dust.

[j] Doses estimated on basis of grab samples.

[k] The contribution of dust is small because of the low grade of the ore and has been ignored.

[l] Because of uncertainties in the fraction of the total doses to workers in uranium milling and extraction, these data have not been included in the summation of doses over countries.

[m] Data from [E1, E2, E3]; some of the data include only workers exposed in excess of 0.1 WLM.

[n] Tabulated data on uranium milled, number of workers, doses and distribution ratios comprise the sum or averages of data for Argentina, Canada, Czechoslovakia, France, the German Democratic Republic, India and the United States (i.e. those countries for which data for at least one period are complete in terms of these quantities); the percentage contributions to exposure pathways are averaged over Australia, Canada, Czechoslovakia, the German Democratic Republic and India. 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.

[o] Estimates extrapolated from total of reported data, based on total uranium milled (assumed to be the same as the uranium mined in the same period) worldwide relative to that milled in reporting countries.

Table 5
Exposures from uranium enrichment [a]
Data from UNSCEAR Survey of Occupational Exposures unless otherwise indicated

Country and period	Annual amount of separative work (MSWU)	Average enrichment (%)	Equivalent amount of energy [b] (GW a)	Monitored workers (thousands)	Measurably exposed workers (thousands)	Annual collective effective dose			Average annual effective dose		Distribution ratio	
						Total (man Sv)	Average per unit separative work (man Sv MSWU^{-1})	Average per unit energy generated [man Sv (GW a)$^{-1}$]	Per monitored worker (mSv)	Per measurably exposed worker (mSv)	NR_{15} [c]	SR_{15}
France [d] [P2]												
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	0.008	0.003			0.002	0.37	0	
Japan [d]												
1987-1989	0.2			0.14		0.00			0		0	
Netherlands [d]												
1985-1989		2.8		0.01		0.01			0.69		0	0
South Africa [d e]												
1975-1979				0.05		0.006			0.13		0	0
1980-1984				0.12		0.013			0.11		0	0
1985-1989	0.10	3.25	0.78	0.09		0.035	0.341	0.044	0.38		0	0
United Kingdom [d f] [B8]												
1975-1979	0.33	1.5	2.50	0.35		0.142	0.438	0.057	0.41			
1980-1982	0.18	0.7	1.41	0.25		0.107	0.584	0.076	0.42			
United Kingdom [d f] [B8]												
1975-1979	0.06	2.52	0.47	0.35		0.040	0.665	0.086	0.12			
1980-1984	0.29	2.88	2.23	0.22		0.049	0.170	0.022	0.22			
1985-1989	0.63	3.12	5.11	0.16		0.023	0.037	0.005	0.15			
United States [d] [E1]												
1975-1979				10.3	8.34	5.14			0.50	0.62	0	0
1980-1984				1.45	0.65	0.62			0.42	0.94	0	0
1985-1989				2.92	0.93	0.36			0.12	0.38	0	0
Total of reported data [g]												
1975-1979				11		5.3			0.46		0	0
1980-1984				4.3		0.78			0.18		0	0
1985-1989				5.0		0.43			0.08		0	0

[a] The data are annual values averaged over the indicated periods.
[b] Estimated on the simplifying assumption that all the enriched uranium is used in LWRs. The assumed fuel cycle requirement is 0.13 MSWU (GW a)$^{-1}$.
[c] The values of NR_{15} are for the monitored workforce. Values for the exposed workforce can also be estimated where data are given for both monitored and measurably exposed workers.
[d] Enrichment by diffusion process [France, United Kingdom (first entry), United States]; centrifuge process [Japan, Netherlands, United Kingdom (second entry)]; jet nozzle process (South Africa).
[e] Pilot facility operations only before 1988. Data for separative work, energy equivalent and normalized collective doses are averages over the years 1988 and 1989.
[f] Data are for enrichment only and do not include doses from uranium conversion to uranium hexafluoride. From 1986 onwards doses have been formally estimated and are included in the statistics where they exceed the defined recording level; no internal doses above the recording level were received in 1986-1990.
[g] These data should be interpreted with care, particularly when making comparisons 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 much less complete than data for the other quantities.

Table 6
Exposures from fuel fabrication [a]
Data from UNSCEAR Survey of Occupational Exposures unless otherwise indicated

Country and period	Annual amount of fuel fabricated (kt)	Equivalent amount of energy [b] (GW a)	Monitored workers (thousands)	Measurably exposed workers (thousands)	Annual collective effective dose			Average annual effective dose		Distribution ratio	
					Total (man Sv)	Average per fuel fabricated (man Sv per kt)	Average per unit energy generated [man Sv (GW a)$^{-1}$]	Per monitored worker (mSv)	Per measurably exposed worker (mSv)	NR_{15} [c]	SR_{15}
LWR fuel											
Japan [d]											
1979	0.82	14.5	1.02		0.54	0.66	0.037	0.53		0	
1980-1984	1.06	18.1	1.44		0.86	0.82	0.048	0.60		0	
1985-1989	1.28	20.7	1.67		0.52	0.40	0.025	0.31		0	
Republic of Korea											
1988-1989	0.03	0.87	0.20		0.06	1.83	0.068	0.30		0	0
Spain											
1986-1989	0.16	4.43	0.35	0.25	0.38	2.33	0.086	1.09	1.53		
Sweden											
1986, 1988-1989	0.26	7.01	0.35	0.09	0.21	0.82	0.030	0.61	2.29		
United States [e,f]											
1975-1979	0.95	25.8	11.1	5.85	19.0	19.8	0.734	1.71	3.24	0.013	0.39
1980-1984	1.19	32.3	9.45	5.49	8.68	7.26	0.269	0.92	1.58	0.003	0.12
1985-1989	1.92	51.8	9.95	3.88	4.51	2.35	0.087	0.45	1.16	0.0003	0.014
Total of reported data [g]											
1975-1979	1.12	28.7	11.3		19.1	17.0	0.664	1.69		0.013	0.39
1980-1984	2.25	50.4	10.9		9.54	4.23	0.189	0.88		0.003	0.12
1985-1989	3.50	80.6	12.2		5.48	1.57	0.068	0.45		0.0003	0.015
World [h]											
1975-1979	1.6	42	17		29	18	0.69	1.7			
1980-1984	3.7	81	17		15	4.1	0.19	0.87			
1985-1989	6.8	160	24		11	1.6	0.069	0.45			

Table 6 (continued)

Country and period	*Annual amount of fuel fabricated (kt)*	*Equivalent amount of energy* [b] *(GW a)*	*Monitored workers (thousands)*	*Measurably exposed workers (thousands)*	*Annual collective effective dose*			*Average annual effective dose*		*Distribution ratio*	
					Total (man Sv)	*Average per fuel fabricated (man Sv per kt)*	*Average per unit energy generated [man Sv (GW a)$^{-1}$]*	*Per monitored worker (mSv)*	*Per measurably exposed worker (mSv)*	NR_{15} [c]	SR_{15}
HWR fuel											
Argentina [i]											
1980-1984	0.030	0.138	0.104		0.025	0.838	0.180	0.24			
1985-1989	0.046	0.218	0.107		0.024	0.513	0.109	0.22			
Canada [j]											
1975-1979	0.61	3.38	0.53	0.34	0.68	1.12	0.202	1.27	1.99	0.005	0.10
1980-1984	1.13	6.30	0.65	0.36	0.95	0.84	0.151	1.48	2.64	0.0003	0.003
1985-1989	1.41	7.81	0.43	0.28	1.02	0.73	0.131	2.37	3.62	0.0009	0.006
India [k]											
1981-1984	0.02	0.13	0.40	0.11	0.11	4.5	0.82	0.28	1.04	0	0
1985-1989	0.06	0.31	0.50	0.44	0.80	14.1	2.54	1.59	1.81	0.004	0.074
Republic of Korea											
1985-1989	0.06	0.33	0.10	0.03	0.06	0.93	0.168	0.58	2.12	0.002	0.22
Total HWR fuel [l]											
1975-1979	0.61	3.38	0.53		0.68	1.12	0.202	1.27		0.005	0.10
1980-1984	1.18	6.54	1.07		1.06	0.90	0.163	1.00		0.0002	0.002
1985-1989	1.57	8.67	1.14		1.90	1.21	0.219	1.67		0.003	0.042
Magnox fuel											
United Kingdom [B8] and total Magnox [m]											
1975-1979	0.95	2.87	0.88		2.03	2.14	0.708	2.30		0.003	
1980-1984	0.80	2.43	1.00		1.96	2.44	0.806	1.95		0.002	
1985-1989	0.81	2.46	1.11		3.48	4.29	1.42	3.12		0.018 [n]	
AGR fuel											
United Kingdom [B8] and total AGR fuel [o]											
1975-1979	0.44	11.6	1.68		3.76	8.57	0.325	2.24		0.002	
1980-1984	0.40	10.5	1.91		3.20	8.03	0.305	1.67		0.001	
1985-1989	0.46	12.2	1.85		5.51	11.9	0.454	2.97		0.014 [n]	

Table 6 (continued)

Country and period	Annual amount of fuel fabricated (kt)	Equivalent amount of energy [b] (GW a)	Monitored workers (thousands)	Measurably exposed workers (thousands)	Annual collective effective dose			Average annual effective dose		Distribution ratio	
					Total (man Sv)	Average per fuel fabricated (man Sv per kt)	Average per unit energy generated [man Sv (GW a)$^{-1}$]	Per monitored worker (mSv)	Per measurably exposed worker (mSv)	NR_{15} [c]	SR_{15}
FBR fuel											
Japan											
1975-1979	0.01		0.42		0.15	30.14		0.36		0	
1980-1984	0.01		0.69		0.52	68.81		0.75		0	
1985-1989	0.01		0.99		0.48	90.53		0.48		0	

[a] The data are annual values averaged over the indicated periods. Contributions of internal exposures to doses are included for Spain (32%), Canada (0%) and United Kingdom (35% average for both types of fuel in 1985-1989). All other doses are from external exposure only.

[b] The amounts of fuel (uranium) 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.

[c] The values of NR_{15} are for the monitored workforce. Values for the exposed workforce can also be estimated where data are given for both monitored and measurably exposed workers.

[d] Internal exposure negligible.

[e] Summary data from annual reports of the United States Nuclear Regulatory Commission. The data for 1975-1981 include exposures during fuel reprocessing. The distribution ratios are not reported formally by United States Nuclear Regulatory Commission licensees. They have been estimated as the mean of the distribution ratios for individual doses of 10 and 20 mSv. This approximation will, in general, cause the tabulated distribution ratios to be overestimates because many occupational exposure dose distributions are log-normal.

[f] No data were available for the annual production of fuel. In their absence, annual fuel production was assumed to be equivalent to the energy generated in the respective years by LWRs in the United States. This assumption is likely to underestimate the fuel produced (and overestimate the normalized collective doses) as some of the fuel was used in reactors outside the United States; moreover, fuel production and energy generation are not contemporaneous.

[g] These data should be interpreted with care, particularly when making comparisons 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 much less complete than data on the other quantities.

[h] The reported data have been scaled by the ratio of the worldwide production of fuel to that included in the reported data; in the absence of data on worldwide fuel production, this was assumed to be the annual fuel requirement needed to generate the electrical energy produced by LWRs in the same year. In the absence of better data, the values of the ratios NR_{15} and SR_{15}, averaged over the reported data, can be considered indicative of worldwide levels.

[i] Contribution from internal exposure not included but estimated to be less than 10%.

[j] NR distribution ratios reported for measurably exposed workers adjusted for monitored workforce.

[k] No data reported on the amount of fuel fabricated; assumed to be that needed for the actual generation of energy in India in each period by the particular reactor type.

[l] The countries reporting data are assumed to represent the total worldwide production of fuel of this type.

[m] Some GCR fuel has been fabricated in other countries, but the amount is small in comparison with that fabricated in the United Kingdom and has been ignored.

[n] Internal exposures were included in the reported doses for 1985-1989, but not for earlier periods; the increase in the distribution ratio is more apparent than real.

[o] Data include workers associated with and doses incurred in fuel fabrication and the conversion of uranium to and from uranium hexafluoride for enrichment. About 5% of the collective dose arises during conversion but data on the fraction of the workforce involved in the respective activities are not available; the average individual doses in conversion and fabrication are similar. The data are mainly for the fabrication of AGR fuel, but about 10% of the production is PWR fuel.

Table 7
Summary of worldwide exposures from fuel fabrication [a]

Fuel type	*Annual amount of fuel fabricated* (kt)	*Equivalent amount of energy* [b] (GW a)	*Monitored workers* (thousands)	*Average annual collective effective dose* (man Sv)	*Collective effective dose per unit mass of fuel* (man Sv kt^{-1})	*Collective effective dose per unit energy generated* [man Sv $(GW\ a)^{-1}$]	*Average annual effective dose to monitored workers* (mSv)	*Distribution ratio* NR_{15}	*Distribution ratio* SR_{15}
1975-1979									
LWR	1.6	42	17	29	18	0.69	1.7	0.013	0.39
HWR	0.61	3.4	0.53	0.68	1.1	0.2	1.3	0.005	0.10
Magnox	0.95	2.9	0.88	2.0	2.1	0.71	2.3	0.003	
AGR	0.44	12	1.7	3.8	8.6	0.33	2.2	0.002	
Total		60	20	36		0.59	1.8	0.012	0.38
1980-1984									
LWR	3.7	81	17	15	4.1	0.19	0.87	0.003	0.12
HWR	1.2	6.5	1.1	1.1	0.90	0.16	1.0	0.0002	0.002
Magnox	0.80	2.43	1.0	2.0	2.4	0.81	2.0	0.002	
AGR	0.40	11	1.9	3.2	8.0	0.31	1.7	0.001	
Total		100	21	21		0.21	1.0	0.002	0.11
1985-1989									
LWR	6.8	160	24	11	1.6	0.07	0.45	0.0003	0.015
HWR	1.6	8.7	1.1	1.9	1.2	0.22	1.7	0.003	0.042
Magnox	0.81	2.5	1.1	3.5	4.3	1.4	3.1	0.018 [c]	
AGR	0.46	12	1.9	5.5	12	0.45	3.0	0.014 [c]	
Total		180	28	22		0.12	0.78	0.002	0.019

[a] The data are annual values averaged over the indicated periods.

[b] The amounts of fuel (uranium) 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.

[c] The value for NR_{15} for Magnox and AGR fuel for the period 1985-1090 take account of internal exposures which were not included in earlier periods. The increases in the NR in 1985-1989 are therefore apparent rather than real.

Table 8
Exposures at reactors [a]
Data from UNSCEAR Survey of Occupational Exposures unless otherwise indicated

Country and period	Average number of reactors over the period	Installed capacity (GW)	Energy generated [b] (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 (GW a)$^{-1}$]	Average annual effective dose: Per monitored worker (mSv)	Average annual effective dose: Per measurably exposed worker (mSv)	Distribution ratio: NR_{15} [c]	Distribution ratio: SR_{15}
PWRs												
Belgium [d] [B5]												
1975-1979	4.0	1.67	1.14	2.39		5.28	1.32	4.63	2.21			
1980-1984	5.2	2.75	2.01	4.50		10.1	1.94	5.00	2.24			
1985-1989	7.6	5.49	4.26	8.38		17.9	2.36	4.22	2.14			
China (Taiwan Province)												
1984	1.0	0.95	0.34	3.68		0.26	0.26	0.77	0.07			
1985-1989	2.0	1.90	1.06	2.52		1.41	0.71	1.34	0.56			
Czechoslovakia												
1975-1977	1.0	0.41	0.11	0.87	0.08	0.09	0.09	0.79	0.10	1.17	0.001	0.12
1980-1984	2.2	0.90	0.62	1.56	0.80	1.84	0.83	2.97	1.18	2.30	0.010	0.17
1985-1989	7.0	2.94	2.11	4.14	2.43	3.97	0.57	1.88	0.96	1.64	0.005	0.12
Finland												
1977-1979	1.0	0.47	0.34	0.93	0.47	0.79	0.79	2.31	0.84	1.69	0	0
1980-1984	1.8	0.84	0.67	1.26	0.73	1.80	1.00	2.71	1.43	2.48	0.006	0.072
1985-1989	2.0	0.93	0.84	1.09	0.65	1.73	0.87	2.05	1.59	2.66	0.007	0.073
France [e]												
1977-1979	3.5	3.15	1.93	3.40	0.89	4.34	1.24	2.24	1.28	4.87		
1980-1984	17.2	15.5	11.1	14.4	6.40	29.4	1.71	2.65	2.05	4.60	0.032	
1985-1989	41.0	40.1	28.3	29.7	16.8	78.9	1.92	2.79	2.65	4.68	0.047	
German Dem. Rep.												
1975-1979	4.0	1.39	0.60	3.41		5.10	1.28	8.48	1.50		0.036	0.45
1980-1984	5.0	1.83	1.33	3.12		8.65	1.73	6.49	2.77		0.060	0.44
1985-1989	5.0	1.83	1.35	3.80	1.58	9.24	1.85	6.86	2.43	5.85	0.050	0.42
Germany, Fed. Rep. of												
1975-1979	4.8	3.94	2.71	3.91		17.5	3.64	6.45	4.47			
1980-1984	6.6	6.46	5.03	8.54		34.4	5.21	6.83	4.02			
1985-1989	11.4	12.9	9.53	15.2		32.6	2.86	3.43	2.15			

Table 8 (continued)

Country and period	*Average number of reactors over the period*	*Installed capacity* (GW)	*Energy generated* [b] (GW a)	*Monitored workers* (thousands)	*Measurably exposed workers* (thousands)	*Annual collective effective dose*			*Average annual effective dose*		*Distribution ratio*	
						Total (man Sv)	*Average per reactor* (man Sv)	*Average per unit energy generated* [man Sv (GW a)$^{-1}$]	*Per monitored worker* (mSv)	*Per measurably exposed worker* (mSv)	NR_{15} [c]	SR_{15}
Hungary												
1983-1984	1.5	0.66	0.36	1.26	0.29	0.32	0.21	0.89	0.25	1.09	0	0
1985-1989	3.4	1.50	1.19	2.81	0.99	1.70	0.50	1.43	0.61	1.72	0.002	0.053
Japan												
1975-1979	7.0	4.76	2.02	7.21	6.11	14.1	2.02	6.99	1.96	2.32	0.020	0.18
1980-1984	11.8	8.69	5.44	13.2	9.22	30.7	2.60	5.65	2.32	3.33	0.020	0.16
1985-1989	16.2	12.6	9.22	18.6	12.1	33.5	2.07	3.63	1.80	2.76	0.012	0.12
Netherlands												
1975-1979	1.0	0.48	0.37	0.60		4.10	4.10	11.0	6.89		0.136	0.44
1980-1984	1.0	0.48	0.39	0.96		3.58	3.58	9.24	3.75		0.057	0.30
1985-1989	1.0	0.48	0.39	1.14		2.83	2.83	7.21	2.48		0.018	0.15
Republic of Korea												
1977-1979	1.0	0.59	0.27	0.48		1.66	1.66	6.09	3.49			
1980-1984	1.4	0.85	0.54	0.96		4.50	3.21	8.32	4.67			
1985-1989	5.8	4.65	3.32	4.67		12.8	2.20	3.85	2.73			
South Africa												
1984	2.0	1.92	0.45	1.72	0.08	0.12	0.06	0.27	0.07	1.45	0.001	0.29
1985-1989	2.0	1.92	0.96	1.72	0.59	1.61	0.81	1.68	0.94	2.75	0.008	0.18
Spain [f]												
1975-1979	1.0	0.16	0.13	0.22		2.60	2.60	20.7	11.7			
1980-1984	2.6	1.65	0.67	1.51		6.76	2.60	10.1	4.21			
1985-1989	5.6	4.51	3.25	5.30	3.81	17.7	3.17	5.45	3.35	4.65		
Sweden [g]												
1975-1979	1.0	0.80	0.47		0.62	1.52	1.52	3.28		2.46	0.027	0.24
1980-1984	2.2	1.88	0.87		0.97	3.58	1.63	4.10		3.68	0.033	0.27
1985-1989	3.0	2.60	1.93		1.82	4.80	1.60	2.49		2.65	0.027	0.19
Switzerland												
1975-1979	2.2	0.89	0.71	0.63		4.16	1.89	5.83	6.64			
1980-1984	3.0	1.64	1.44	1.49		7.46	2.49	5.20	5.01			
1985-1989	3.0	1.64	1.44	1.67		6.60	2.20	4.58	3.95			

Table 8 (continued)

Country and period	*Average number of reactors over the period*	*Installed capacity* (GW)	*Energy generated* [b] (GW a)	*Monitored workers* (thousands)	*Measurably exposed workers* (thousands)	*Annual collective effective dose*			*Average annual effective dose*		*Distribution ratio*	
						Total (man Sv)	*Average per reactor* (man Sv)	*Average per unit energy generated* [man Sv (GW a)$^{-1}$]	*Per monitored worker* (mSv)	*Per measurably exposed worker* (mSv)	NR_{15} [c]	SR_{15}
USSR [h] [B11, I9]												
1978-1979	7.5	2.7	1.7	3.2		19.4	2.59	11.2	6.14			
1980-1984	12.8	5.9	3.8	6.6		32.8	2.56	8.66	4.99			
1985-1987	22.0	13.9	8.7	12.3		57.1	2.60	6.55	4.63			
United States [i]												
1975-1979	34.2	25.2	16.2	38.8	22.8	147	4.31	9.13	3.80	6.47	0.089	0.57
1980-1984	46.8	38.7	22.1	83.1	51.0	276	5.89	12.5	3.32	5.41	0.075	0.53
1985-1989	63.0	59.1	37.4	109.2	61.4	225	3.58	6.02	2.06	3.67	0.036	0.36
Total of reported data [j]												
1975-1979	64.4	42.4	26.1	60.9		212	3.29	8.13	3.48		0.085	0.56
1980-1984	121	86.8	56.3	144		451	3.73	8.01	3.14		0.061	0.48
1985-1989	192	159	112	219		487	2.53	4.36	2.22		0.034	0.32
World [k]												
1975-1979	78	49	27	63		220	2.8	8.1	3.5		0.085	0.56
1980-1984	140	98	56	140		450	3.3	8.0	3.1		0.061	0.48
1985-1989	220	180	120	230		500	2.3	4.3	2.2		0.034	0.32
BWRs												
China (Taiwan Province)												
1981-1984	3.8	3.00	1.83	6.32		14.4	3.84	7.85	2.28			
1985-1989	4.0	3.24	2.32	6.69		18.2	4.55	7.84	2.72			
Finland												
1978-1979	1.0	0.68	0.21	1.44	0.29	0.12	0.12	0.55	0.08	0.40	0	0
1980-1984	2.0	1.36	1.02	1.61	0.88	0.87	0.44	0.86	0.54	0.99	0.000	0.004
1985-1989	2.0	1.47	1.33	1.92	1.14	1.80	0.90	1.36	0.94	1.59	0.002	0.033
Germany, Fed. Rep. of												
1975-1979	3.0	1.65	0.72	3.74		19.9	6.64	27.8	5.33			
1980-1984	4.4	3.80	2.12	10.2		33.4	7.59	15.7	3.28			
1985-1989	7.0	7.21	5.68	12.4		19.4	2.78	3.42	1.56			
India												
1980-1984	2.0	0.410	0.201	3.35	3.30	38.0	19.0	189	11.4	11.5	0.241	
1985-1989	2.0	0.304	0.205	2.69	2.56	23.2	11.6	113	8.63	9.06	0.157	

Table 8 (continued)

Country and period	Average number of reactors over the period	Installed capacity (GW)	Energy generated [b] (GW a)	Monitored workers (thousands)	Measurably exposed workers (thousands)	Annual collective effective dose			Average annual effective dose		Distribution ratio	
						Total (man Sv)	Average per reactor (man Sv)	Average per unit energy generated [man Sv (GW a)$^{-1}$]	Per monitored worker (mSv)	Per measurably exposed worker (mSv)	NR_{15} [c]	SR_{15}
Japan												
1975-1979	7.8	5.01	2.30	17.7	18.2	72.9	9.35	31.6	4.12	4.01	0.072	0.34
1980-1984	13.0	9.95	6.24	27.4	18.9	91.4	7.03	14.6	3.34	4.83	0.057	0.34
1985-1989	18.4	15.4	10.6	34.8	20.7	63.6	3.46	6.02	1.83	3.07	0.018	0.20
Netherlands												
1975-1979	1.0	0.054	0.047	0.28		2.31	2.31	49.2	8.38		0.202	0.24
1980-1984	1.0	0.054	0.047	0.47		2.24	2.24	48.1	4.81		0.114	0.27
1985-1989	1.0	0.054	0.049	0.56		1.62	1.62	32.9	2.87		0.038	0.19
Spain [l]												
1975-1979	1.0	0.46	0.32	0.62		5.36	5.36	16.8	8.60			
1980-1984	1.2	0.66	0.27	0.97		7.85	6.54	29.2	8.08			
1985-1989	2.0	1.44	1.09	2.66	2.06	10.1	5.05	9.26	3.80	4.90		
Sweden [l]												
1975-1979	4.6	2.66	1.64		2.09	5.98	1.3	3.65		2.86	0.027	0.24
1980-1984	6.6	4.34	3.46		3.13	8.22	1.25	2.38		2.63	0.033	0.27
1985-1989	9.0	7.02	5.64		3.71	10.7	1.19	1.89		2.88	0.027	0.19
United States [i]												
1975-1979	22.8	14.6	9.37	33.3	19.9	156	6.83	16.6	4.68	7.84	0.064	0.65
1980-1984	26.2	17.9	10.4	53.3	35.1	268	10.2	25.7	5.03	7.63	0.084	0.63
1985-1989	32.2	26.5	14.7	77.2	40.5	181	5.63	12.3	2.35	4.48	0.026	0.43
Total of reported data [l]												
1975-1979	40.6	24.7	14.3	55.9		262	6.46	18.1	4.69		0.066	0.61
1980-1984	59.0	40.8	25.2	102		454	7.69	18.0	4.47		0.079	0.55
1985-1989	77.6	62.6	41.6	139		330	4.25	7.93	2.38		0.026	0.36
World [k]												
1975-1979	51.2	29.3	15.3	59.2		279	5.45	18.3	4.71		0.066	0.61
1980-1984	64.6	44.1	25.1	102		454	7.00	18.0	4.47		0.079	0.55
1985-1989	83.8	66.9	41.8	139		331	3.96	7.94	2.38		0.026	0.36
HWRs												
Argentina [m]												
1975-1979	1.0	0.33	0.26	0.43		4.52	4.52	17.2	10.5		0.26	0.73
1980-1984	1.4	0.59	0.32	0.77		8.04	5.74	25.2	10.5		0.27	0.79
1985-1989	2	0.98	0.61	1.06		12.6	6.29	20.8	11.9		0.29	0.80

Table 8 (continued)

Country and period	*Average number of reactors over the period*	*Installed capacity* (GW)	*Energy generated* [b] (GW a)	*Monitored workers* (thousands)	*Measurably exposed workers* (thousands)	*Annual collective effective dose*			*Average annual effective dose*		*Distribution ratio*	
						Total (man Sv)	*Average per reactor* (man Sv)	*Average per unit energy generated* [man Sv (GW a)$^{-1}$]	*Per monitored worker* (mSv)	*Per measurably exposed worker* (mSv)	NR_{15} [c]	SR_{15}
Canada												
1975-1979	8.4	4.32	2.45	5.65	2.62	24.0	2.85	9.77	4.24	9.15	0.11	0.70
1980-1984	13	7.41	4.53	9.27	3.54	20.1	1.57	4.43	2.16	5.67	0.046	0.49
1985-1989	18	11.6	8.03	11.0	4.61	16.7	0.94	2.07	1.51	3.61	0.017	0.23
Czechoslovakia [n]												
1975-1979	1			0.85	0.65	4.61	4.61		5.42	7.03	0.11	0.58
1980-1984	1			0.51	0.36	0.77	0.77		1.51	2.13	0.015	0.22
1985-1989	1			0.54	0.31	0.88	0.88		1.62	2.83	0.020	0.24
India												
1981-1984	2.5	0.51	0.15	3.09	2.19	15.7	6.28	103	5.08	7.17	0.11	
1985-1989	4.2	0.83	0.38	4.40	3.88	28.7	6.83	76	6.51	7.39	0.13	
Republic of Korea												
1983-1984	1	0.68	0.41	0.72		0.65	0.65	1.58	0.90			
1985-1989	1	0.68	0.59	0.81		1.13	1.13	1.91	1.40			
Total of reported data [k o]												
1975-1979	9.40	4.65	2.71	6.08		28.5	3.03	10.5	4.68		0.12	0.71
1980-1984	16.6	8.68	5.13	12.8		40.9	2.47	7.97	3.20		0.073	0.58
1985-1989	25.0	14.1	9.61	17.3		59.0	2.36	6.14	3.41		0.066	0.48
World [l]												
1975-1979	12	5.0	3.1	6.8		32	2.6	11	4.8		0.12	0.71
1980-1984	19	9.0	5.7	14		46	2.4	8.0	3.2		0.073	0.58
1985-1989	26	14	9.8	18		60	2.3	6.2	3.4		0.066	0.48
GCRs												
Japan												
1979	1	0.2	0.1	1.59	0.81	1	1	10	0.63	1.23	0.001	
1980-1984	1	0.2	0.1	2.13	0.95	1	1	10	0.47	1.05	0.0014	0.023
1985-1989	1	0.2	0.1	2.01	0.84	1	1	10	0.50	1.19	0.0002	0.008
Spain												
1975-1979	1	0.48	0.37	0.07		0.30	0.30	0.80	3.98			
1980-1984	1	0.48	0.36	0.18		0.37	0.37	1.02	2.08			
1985-1989	1	0.48	0.33	0.25	0.13	0.28	0.28	0.85	1.12	2.18		

Table 8 (continued)

Country and period	Average number of reactors over the period	Installed capacity (GW)	Energy generated [b] (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 (GW a)$^{-1}$]	Average annual effective dose: Per monitored worker (mSv)	Average annual effective dose: Per measurably exposed worker (mSv)	Distribution ratio: NR_{15} [c]	Distribution ratio: SR_{15}
United Kingdom [p]												
1975-1979	30	6.04	3.40	8.56		24.5	0.82	7.20	2.86		0.02	
1980-1984	32	7.40	4.40	18.0		26.4	0.82	6.00	1.46		0.0054	
1985-1989	37	10.4	6.09	25.4		19.5	0.52	3.20	0.77		0.0002	
Total of reported data [k]												
1975-1979	31.2	6.56	3.79	8.95		25.0	0.80	6.59	2.80		0.020	
1980-1984	34.0	8.08	4.86	20.3		27.8	0.82	5.72	1.37		0.005	
1985-1989	39.2	11.1	6.52	27.6		20.8	0.53	3.19	0.75		0.0002	0.008
World [l]												
1975-1979	40	9.1	5.4	13		36	0.90	6.6	2.8			
1980-1984	41	10	6.0	25		34	0.84	5.8	1.4			
1985-1989	44	13.3	7.4	31		24	0.54	3.2	0.75			
Prototype FBRs												
France												
1986-1989	1	1.10	0.094	0.50		0.033	0.033	0.351	0.067			
USSR (BR350) [q] [B11]												
1978-1979	1	0.35 [r]		0.59		0.61	0.61		1.03			
1980-1984	1	0.35		0.60		0.81	0.81		0.35			
1985-1987	1	0.35		0.49		0.98	0.98		2.00			
USSR (BR600) [B11]												
1980-1984	1	0.6	0.34	0.92		0.40	0.40	1.19	0.43			
1985-1987	1	0.6	0.41	1.08		0.83	0.83	2.04	0.77			
Total of reported data [j] [s]												
1980-1984	1	0.60	0.34	0.92		0.40	0.40	1.19	0.43			
1985-1989	1.4	1.24	0.32	1.04		0.52	0.37	1.64	0.50			
World [k] [s]												
1980-1984	4.0	1.0	0.50	1.4		0.61	0.15	1.2	0.44			
1985-1989	4.8	1.9	0.73	2.1		1.0	0.21	1.4	0.48			
LWGRs												
World [t]												
1978-1979	12	5.9	4.35	5.37		35.6	2.97	8.18	6.64			
1980-1984	16.2	10.1	7.50	9.80		62.2	3.84	8.30	6.35			
1985-1987	20	14.7	10.4	13.1		173	8.67	16.7	13.2			

Table 8 (continued)

Country and period	Average number of reactors over the period	Installed capacity (GW)	Energy generated [b] (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 (GW a)$^{-1}$]	Average annual effective dose: Per monitored worker (mSv)	Average annual effective dose: Per measurably exposed worker (mSv)	Distribution ratio: NR_{15} [c]	Distribution ratio: SR_{15}
HTGRs												
World [a]												
1975-1979	1	0.33	0.034	1.15	0.059	0.031	0.031	0.90	0.027	0.52		
1980-1984	1	0.33	0.071	1.16	0.046	0.017	0.017	0.24	0.015	0.37		
1985-1989	1	0.33	0.030	0.78	0.148	0.097	0.097	3.25	0.124	0.65		

[a] The data are annual values averaged over the periods indicated.
[b] Data on energy generated taken, unless otherwise indicated, from responses to questionnaire or from [I8].
[c] The values of NR_{15} are for the monitored workforce. Values for the exposed workforce can also be estimated where data are given for both monitored and measurably exposed workers.
[d] The numbers of workers include utility workers and contractor workers. Data on number of reactors, installed capacity and energy generated from [I8].
[e] Additional data from [B5, B6]. The reported data are for utility workers, except for collective doses, which are for utility and contractor workers. Additional data have been reported on the exposure of about 30%-40% of contractors [L2, P2]. The numbers of workers and average doses tabulated have been estimated from the reported annual collective doses for the whole workforce (i.e. utility workers and contractor workers), subject to the assumption that the exposures reported for a fraction of the contractor workers are representative of the contractor workers as a whole. The average doses to utility workers are significantly lower than those to contractor workers. During the 1980s the average annual dose to monitored utility workers was about 1 mSv and to monitored contractors about 4 mSv; the corresponding doses to measurably exposed workers were about 2 mSv and 7 mSv, respectively.
[f] Data include both utility workers and contractor workers.
[g] Data on numbers of workers are from [B5]. The distribution ratios are averages for Swedish LWRs overall rather than for PWRs.
[h] The data have been scaled, on the basis of energy generated, from those reported, which did not cover all PWRs in the USSR.
[i] Summary data from annual reports of USNRC. Data are uncorrected for the reporting of transient workers. The NR ratios are for the monitored workforce and have been derived from the ratios reported by [R2] for the measurably exposed workforce. The distribution ratios are not reported formally by USNRC licensees. They have been estimated [R2] as the mean of the distribution ratios for individual doses of 10 and 20 mSv. This approximation will, in general, cause the tabulated distribution ratios to be overestimates because many occupational exposure dose distributions are log-normal.
[j] 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 much less complete than data on the other quantities.
[k] These data are the sum of reported data above scaled to account for missing data; the numbers of monitored workers and the collective doses have been scaled on the basis of the total energy generated by the respective reactor type and that for the reported data. In the absence of better data, the values of the ratios NR_{15} and SR_{15}, averaged over the reported data, can be considered indicative of worldwide levels.
[l] Data available are averages for LWRs as a whole and not separately for PWRs and BWRs.
[m] During the early 1980s administrative constraints were placed on energy generation by nuclear means; as a consequence, collective doses per unit energy generation are higher than they would have otherwise been.
[n] Data are for a HWGCR (all the other entries in the Table are for water-cooled reactors); data for NR_{15} and SR_{15} are for measurably exposed workers.
[o] Sum of reported data, excluding Czechoslovakia.
[p] Data included for all commercial GCRs in the United Kingdom, including Magnox and AGRs; data for the various types of GCRs differ significantly and are summarized in Table 11.
[q] The plant is used for desalination.
[r] Thermal installed capacity.
[s] Excluding the USSR/BR350, which is a desalination plant.
[t] These data have been scaled on the basis of total energy generated compared to that for the reported data, which did not cover all LWGRs in the USSR.
[u] These data are for the Fort St. Vrain prototype reactor; there were not enough data to allow estimating worldwide doses from other prototype HTGRs.

Table 9
Dose distribution ratios for measurably exposed LWR workers in the United States [B2, R2]

Year	*Percentage of workers receiving annual effective dose above specified values (NR_E × 100)*				
	1 mSv	*5 mSv*	*10 mSv*	*15 mSv*	*30 mSv*
1973	63	43	34	24	6.3
1977	67	40	26	17	4.7
1981	64	37	23	14	3.0
1985	57	29	16	8.4	0.86
1989	55	22	9.2	3.3	0.10
	Percentage of collective dose from annual individual doses above specified values (SR_E × 100)				
	1 mSv	*5 mSv*	*10 mSv*	*15 mSv*	*30 mSv*
1973	98	93	85	71	30
1977	98	88	76	60	25
1981	97	86	71	52	18
1985	96	80	60	39	6.4
1989	94	70	43	19	0.90

Table 10
Collective effective dose among five occupational groups of LWR workers in the United States in 1987-1989 [B2]

Occupational group	*Monitored workers (thousands)*	*Average annual effective dose to monitored workers (mSv)*	*Average annual collective effective dose* [a] *(man Sv)*
Maintenance	53.8	4.9	263 (66.4)
Health physics	12.5	4.5	55.8 (14)
Operations	10.4	3.2	33.6 (9)
Engineering	10.4	3.1	32.5 (8)
Supervisory	4.56	2.5	11.4 (3)
Total	91.7	4.3	396 (100)

[a] The percentage of the total collective dose is given in parentheses.

Table 11
Exposures to workers in different types of GCRs in the United Kingdom

Type of GCR	*Average annual effective dose per monitored worker (mSv)*			*Average normalized collective effective dose [man Sv (GW a)$^{-1}$]*		
	1975-1979	*1980-1984*	*1985-1989*	*1975-1979*	*1980-1984*	*1985-1989*
Magnox SPC [a]	8.3	9.2	8.2	27	31	27
Magnox SPV [b c]	3.0	1.7	1.1	7.0	9.4	5.8
Magnox CPV [d c]	1.2	0.63	0.15	1.9	1.2	0.57
AGR [c]			0.18			1.1
Average [e]	2.9	1.5	0.77	7.2	6.0	3.2

[a] First-generation Magnox reactors with steel pressure vessels (SPVs); used for defence purposes and generation of electrical energy.
[b] Second-generation commercial Magnox reactors with SPVs [B8].
[c] Average values for reactors operated in England and Wales only [M8].
[d] Third-generation Magnox reactors with concrete pressure vessels (CPVs).
[e] Average values for all types of GCRs in the United Kingdom.

Table 12
Summary of worldwide exposures at reactors [a]

Reactor type	*Average number of reactors*	*Average installed capacity (GW)*	*Average annual energy generated [b] (GW a)*	*Monitored workers [c] (thousands)*	*Average annual collective effective dose [d] (man Sv)*	*Collective effective dose per unit energy genereated [man Sv (GW a)$^{-1}$]*	*Average annual effective dose to monitored workers (mSv)*	*Average annual value of NR_{15} [e]*	*Average annual value of SR_{15}*
1975-1979									
PWR	78	49	27 (49%)	63 (43%)	220 (37%)	8.1	3.5	0.085	0.56
BWR	51	29	15 (27%)	59 (39%)	280 (46%)	18	4.7	0.066	0.61
HWR	12	5.0	3.1 (6%)	6.8 (5%)	32 (5%)	11	4.8	0.12	0.71
LWGR [f]	12	5.9	4.4 (8%)	5.4 (4%)	36 (6%)	8.2	6.6		
GCR	40	9.1	5.4 (10%)	13 (9%)	36 (6%)	6.6	2.8	0.020	
HTGR [g]	1	0.33	0.03	1.2	0.03	0.90	0.03		
Total	190	99	55	150	600	11	4.1	0.078	0.60
1980-1984									
PWR	140	98	56 (55%)	140 (47%)	450 (43%)	8.0	3.1	0.061	0.48
BWR	65	44	25 (25%)	100 (34%)	450 (43%)	18	4.5	0.079	0.55
HWR	19	9.0	5.7 (6%)	14 (5%)	46 (4%)	8.0	3.2	0.073	0.58
LWGR	16	10	7.5 (7%)	9.8 (3%)	62 (6%)	8.3	6.4		
GCR	41	10	6.0 (6%)	25 (8%)	34 (3%)	5.8	1.4	0.005	
FBR	4	1.0	0.50	1.4	0.61	1.2	0.44		
HTGR	1	0.33	0.07	1.2	0.02	0.24	0.01		
Total	280	170	100	290	1000	10	3.5	0.069	0.52
1985-1989									
PWR	220	180	120 (65%)	230 (53%)	500 (46%)	4.3	2.2	0.034	0.32
BWR	84	67	42 (23%)	140 (33%)	330 (30%)	7.9	2.4	0.026	0.36
HWR	26	14	10 (5%)	18 (4%)	60 (6%)	6.2	3.4	0.066	0.48
LWGR [h]	20	15	10 (5%)	13 (3%)	170 (16%)	17	13		
GCR	44	13	7.4 (4%)	31 (7%)	24 (2%)	3.2	0.75	0.0002	0.01
FBR [i]	5	1.9	0.73	2.1	1.0	1.4	0.48		
HTGR	1	0.33	0.03	0.78	0.10	3.3	0.12		
Total	400	290	190	430	1100	5.9	2.5	0.033	0.34

[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 13
Exposures from fuel reprocessing [a]
Data from UNSCEAR Survey of Occupational Exposure unless otherwise indicated

Country and period	Type of fuel	Annual amount of fuel reprocessed (kt)	Equivalent amount of energy from reprocessed fuel (GW a)	Monitored workers (thousands)	Measurably exposed workers (thousands)	Annual collective effective dose			Average annual effective dose		Distribution ratio	
						Total (man Sv)	Average per unit of fuel reprocessed (man Sv kt^{-1})	Average per unit energy generated (man Sv $(GW\ a)^{-1}$)	Per monitored worker (mSv)	Per measurably exposed worker (mSv)	NR_{15} [b]	SR_{15}
France (Cap de La Hague) [c]												
1975-1979	U/Ox	0.360	1.46	1.61	1.09	6.50	0.018	4.45	4.03	5.98	0.056	0.294
1980-1984	U/Ox/Mox	0.375	3.87	2.80	1.73	6.50	0.017	1.68	2.32	3.77	0.013	0.112
1985-1989	U/Ox	0.434	8.85	4.74	2.09	6.74	0.016	0.76	1.42	3.22	0.008	0.116
France (Marcoule) [d]												
1975-1979				2.74	1.88	6.31			2.30	3.36		
1980-1984				3.90	2.16	7.55			1.94	3.50		
1985-1989				4.54	1.77	5.79			1.28	3.27		
India [e]												
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
Japan [f]												
1975-1979	Ox/Mox	0.010		0.84		0.38	0.03		0.44		0	
1980-1984	Ox/Mox	0.030		1.37		1.23	0.04		0.89		0.000	
1985-1989	Ox/Mox	0.052		1.87		1.83	0.03		0.98		0.010	
United Kingdom [g,h]												
1977-1979	U	0.715	2.17	5.61		46.6	65	21.5	8.31		0.193	
1980-1984	U	0.970	2.94	6.62		40.1	41	13.6	6.05		0.143	
1985-1988	U	0.887	2.69	7.22		29.4	33	11.0	4.07		0.101	
United States [i]												
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		
World (metal fuel) [j]												
1975-1979	U	1.1	3.1	7.1		53	50	17	7.4		0.16	
1980-1984	U	1.2	3.6	8.4		44	38	12	5.3		0.12	
1985-1989	U	0.94	2.9	8.0		31	33	11	3.8		0.092	

Table 13 (continued)

Country and period	*Type of fuel*	*Annual amount of fuel reprocessed* (kt)	*Equivalent amount of energy from reprocessed fuel* (GW a)	*Monitored workers* (thousands)	*Measurably exposed workers* (thousands)	*Annual collective effective dose*			*Average annual effective dose*		*Distribution ratio*	
						Total (man Sv)	*Average per unit of fuel reprocessed* (man Sv kt^{-1})	*Average per unit energy generated* [man Sv $(GW\ a)^{-1}$]	*Per monitored worker* (mSv)	*Per measurably exposed worker* (mSv)	NR_{15} [b]	SR_{15}
World (oxide fuel) [i]												
1975-1979	Ox	0.03	0.5	0.1	0.06	0.36	12	0.70	4.0	6.0	0.056	0.29
1980-1984	Ox	0.18	3.2	1.0	0.62	2.4	14	0.75	2.3	3.8	0.013	0.11
1985-1989	Ox	0.38	8.7	4.0	1.8	5.7	15	0.65	1.4	3.2	0.008	0.12

[a] The data are annual values averaged over the respective five-year periods. The doses are from external exposures only, apart from Japan; and the United Kingdom from 1986 onwards.

[b] The values of NR_{15} are 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] Data from [R1] for the UP2 and UP3 plants at Cap de La Hague; reported data identifies amounts of metal, oxide and mixed oxide fuel reprocessed on an annual basis but doses are reported in a combined form for the site as a whole. The total amounts of each type of fuel reprocessed within the respective periods were as follows: 1975-1979, 1,650 t metal, 146 t oxide and 2.2 t mixed oxide; 1980-1984, 1,031 t metal, 836 t oxide and 7.7 t mixed oxide; 1985-1989, 253 t metal and 1,915 t oxide. Reprocessing also undertaken at Marcoule, but data for that site not included here.

[d] Data from [R1]; reprocessing of irradiated fuel from both the commercial and defence fuel cycles.

[e] Data include exposures in reprocessing and waste management.

[f] Data are for a prototype facility; separate data for uranium and mixed oxide fuels unavailable.

[g] The energy generated by reprocessed fuel was estimated from reported ^{85}Kr discharges [B3] on the assumption that 14 PBq of ^{85}Kr are associated with the generation of 1 GW a by Magnox fuel [U1]. The amount of fuel reprocessed was then derived on the basis of 330 t of uranium in Magnox fuel required to generate 1 GW a of electrical energy [O3].

[h] Data from [B8] are for all operations at the Sellafield site apart from the Calder reactors; other activities, unconnected with Magnox reprocessing, are also undertaken at the site and the reported doses will, therefore, be overestimates. Data are for BNFL employees and contractors. Internal doses not explicitly included, but they contribute less than 10% to the total doses. The data for NR_{15} and SR_{15} are taken from [W4] and are for the Sellafield site as a whole (i.e. including the Calder reactors).

[i] Reprocessing at United States Department of Energy facilities and mainly associated with defence activities rather than the commercial nuclear fuel cycle.

[j] Commercial reprocessing has essentially only been carried out in France and the United Kingdom over the period of interest. The data for these countries are combined to provide an overall estimate of the exposures associated with reprocessing metal and oxide fuels. For metal fuel the total comprises the sum of the data from the United Kingdom and that fraction of the data from France that has been estimated as arising from the reprocessing of metal fuel. For oxide fuel the total comprises that fraction of the data for France that can be associated with the reprocessing of oxide fuel.

Table 14
Exposures from commercial nuclear fuel cycle research and development [a] [b]
Data from UNSCEAR Survey of Occupational Exposure unless otherwise indicated

Country and period	Monitored workers (thousands)	Measurably exposed workers (thousands)	Annual collective effective dose (man Sv)	Average annual effective dose		Distribution ratio	
				Per monitored worker (mSv)	Per measurably exposed worker (mSv)	NR_{15} [c]	SR_{15}
Argentina							
1975-1979	0.2	0.01	0.2	1.0	20	0	0
1980-1984	0.2	0.01	0.17	0.85	17	0	0
1985-1989	0.13	0.018	0.07	0.54	3.9	0	0
Canada [d]							
1975-1979	4.49	3.94	13.5	2.95	3.36	0.055	0.44
1980-1984	4.56	4.30	11.1	2.43	2.57	0.043	0.41
1985-1989	4.20	3.97	6.1	1.45	1.54	0.026	0.40
Chile [e]							
1975-1979	0.02	0.02	0.04	2.41	2.41	0.013	0.031
1980-1984	0.03	0.03	0.05	2.00	2.00	0.032	0.11
1985-1989	0.05	0.05	0.06	1.23	1.23	0.017	0.055
Czechoslovakia							
1975-1979	0.36		0.17	0.48		0	0
1980-1984	0.34		0.18	0.52		0	0
1985-1989	0.36		0.13	0.38		0	0
Finland [f]							
1975-1979		0.01	0.01		1.58		0
1980-1984		0.00	0.01		2.58		0
1985-1989		0.01	0.05		3.47		0.25
France							
1975-1979	20.9	3.19	9.32	0.44	2.92	0.005	
1980-1984	21.0	2.86	8.47	0.40	2.97	0.004	
1985-1989	19.6	2.48	6.14	0.31	2.47	0.002	
Germany, Fed. Rep. of [g]							
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 [h]							
1977-1979	0.12	0.01	0.01	0.06	1.49	0	0
1980-1984	0.13	0.01	0.00	0.03	0.83	0	0
1985-1989	0.12	0.01	0.01	0.07	0.96	0	0
India							
1980-1984	2.78	1.97	6.36	2.29	3.23	0.034	0.36
1985-1989	3.62	2.38	4.65	1.28	1.96	0.010	0.18
Indonesia [i]							
1975-1979	0.02		0.09	3.87		0.13	0.37
1980-1984	0.03	0.04	0.10	3.10	2.72	0.16	0.72
1985-1989	0.10	0.10	0.09	0.95	0.95	0.025	0.47
Italy							
1985-1989	2.44	0.45	0.26	0.11	0.58	0.000	0.012
Japan [j]							
1978-1979	4.12		2.13	0.52		0.002	
1980-1984	7.01		7.97	1.14		0.017	
1985-1989	9.18		7.72	0.84		0.008	
Norway [k]							
1980-1984	0.68	0.14	0.53	0.77	3.76	0.008	0.34
1985-1989	0.76	0.15	0.58	0.76	3.88	0.012	0.35

Table 14 (continued)

Country and period	Monitored workers (thousands)	Measurably exposed workers (thousands)	Annual collective effective dose (man Sv)	Average annual effective dose		Distribution ratio	
				Per monitored worker (mSv)	Per measurably exposed worker (mSv)	NR_{15} [c]	SR_{15}
Republic of Korea [l]							
1975-1979	0.25		0.12	0.46		0.004	
1980-1984	0.79	0.14	0.50	0.64	3.58	0.007	
1985-1989	0.99	0.15	0.65	0.65	4.36	0.009	
South Africa							
1975-1979	0.25		0.12	0.46		0.004	0.065
1980-1984	0.24		0.08	0.33		0.004	0.090
1985-1989	0.23		0.07	0.34		0	0
United Kingdom [m]							
1975-1979	8.49		37.4	4.40		0.085	
1980-1984	9.00		28.2	3.13		0.050	
1985-1989	9.40		24.0	2.55		0.033	
United States [n]							
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		
Total of reported data [o]							
1975-1979	63.4		96.3	1.52		0.035	0.42
1980-1984	75.5		89.4	1.18		0.021	0.39
1985-1989	82.6		66.0	0.80		0.011	0.30
World [p]							
1975-1979	120		170	1.4			
1980-1984	130		150	1.1			
1985-1989	130		100	0.82			

[a] The data are annual values averaged over the indicated periods.

[b] Intended to be exposures directly attributable to research and development solely for the commercial nuclear fuel cycle. Because of the way data are collected, there may be contributions from other activities, partial coverage or other inhomogeneities.

[c] The values of NR_{15} are for the monitored workforce. Values for the exposed workforce can also be estimated where data are given for both monitored and measurably exposed workers.

[d] 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.

[e] Includes data for fuel research, a research reactor and radioisotope production.

[f] Comprises only personnel working at one research reactor.

[g] Comprises only workers at research and prototype reactors.

[h] 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.

[i] Comprises data for workers at research reactors.

[j] Comprises exposures of workers at test and research reactors, the nuclear ship, ATR, critical assemblies, and at research facilities for nuclear fuel materials.

[k] Comprises only workers at the Institute of Energy Technology.

[l] Comprises exposures of workers at TRIGA research reactors and other fuel research facilities.

[m] Additional data from [W4]. Most of the exposures arise at AEA Technology (formerly UKAEA) sites, but the contribution from other organizations conducting research and development associated with the nuclear fuel cycle are also included. Almost half the collective dose arises from the operation of the prototype SGHWR.

[n] These data are the sum of exposures of particular categories of employees and contractors of the United States Department of Energy; they include the total exposures attributed by USDOE to fusion and waste management and processing and one half of the exposures attributed to each of the following categories: reactors, general research, offices, maintenance, support and other. This allocation exercise is an attempt to separate out the nuclear fuel cycle component from the broader range of research activities undertaken by USDOE. Some categories of data were excluded from the summation because they were not considered relevant to nuclear fuel cycle research (e.g. weapons fabrication) or were already included in another UNSCEAR category (e.g. accelerators). The tabulated doses are likely to be an overestimate of the doses from research that can properly be attributed to the commercial nuclear fuel cycle.

[o] These data should be interpreted with care, particularly when making comparisons 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 much less complete than data on the other quantities.

[p] In the absence of better data values of the ratios NR_{15} and SR_{15} for the sum of the reported data can be considered indicative of worldwide levels.

Table 15
Predicted cumulative doses for radiation workers in Canada
[S3]

Job classification	*Number of monitored workers*	*Cumulative effective dose (mSv)* [a]	
		Mean	*Median*
Nuclear power station workers			
Chemical and radiation control	240	459	269
Reactor operations	1371	456	321
Mechanical maintenance	1132	454	283
Fuel handling	228	288	152
Control technicians	564	266	173
Training staff	44	240	127
Electrical maintenance	179	222	115
Construction	1008	130	61
Administration/security/janitorial	1339	120	61
General maintenance	1092	116	67
Health physics	60	106	61
Scientific/professional staff	1454	89	54
Total	9391	242	109
Uranium miners	5429	138	90
Nuclear fuel processors	115	166	114
Industrial radiographers	2076	296	131

[a] Cumulative dose over an assumed working lifetime of 40 years.

Table 16
Distribution of cumulative doses to measurably exposed workers at LWRs in the United States who terminated employment between 1977 and 1989
[R2]

Duration of employment (years)		*Average career effective dose (mSv)*	*Percentage of workers with cumulative effective dose above specified values*						
Range	*Average*		*5 mSv*	*10 mSv*	*20 mSv*	*50 mSv*	*100 mSv*	*200 mSv*	*500 mSv*
1-3	1.9	1.02	40.8	29.5	10.6	4.0	0.29	0	0
3-5	4.0	1.63	48.9	37.8	17.9	9.4	2.0	0.07	0.01
5-10	7.2	25.7	60.4	50.2	29.3	18.9	7.1	0.89	0.01
10-15	12.0	43.6	68.0	58.5	39.2	28.2	13.9	3.6	0.09
15-20	16.6	58.0	71.9	62.6	44.4	33.4	18.8	7.1	0.45
20-25	21.8	117	81.3	72.1	59.5	51.8	37.4	19.9	3.1
>25	40.9	74	56.4	47.5	35.9	30.4	20.4	12.2	2.8
All	3.3	14.4	42.1	31.5	13.7	7.7	2.7	0.51	0.02

Table 17
Characteristics of the dose distributions for monitored workers at the Calvert Cliffs nuclear power plant in the United States
[G1]

Parameters	*Contract workers*					*Utility workers*				
	Duration of employment (years)					*Duration of employment (years)*				
	<1	*1-5*	*5-10*	*10-15*	*>15*	*<1*	*1-5*	*5-10*	*10-15*	*>15*
Number of workers	1347	1434	946	146	26	1972	1691	849	203	7
Mean cumulative dose (mSv)	6.5	22	57	78	124	3.4	12	28	37	61 [a]
Percentage of workers with E_c > 50 mSv	0.76	14	42	48	65	0.04	6.1	19	26	57 [a]
Percentage of workers with E_c > 100 mSv	0.53	3.8	23	31	50	0.04	1.6	6.1	9.9	29 [a]
Percentage of workers with E_c > 200 mSv	0.23	0	4.1	11	19	0	0.6	0.6	2.0	0 [c]

[a] Since the estimates are based on only seven workers, the statistical significance is very weak.

Table 18
Number of workers and cumulative doses at the Calvert Cliffs nuclear power plant in the United States
[G1]

Job category	*Number of monitored workers* [a]			*Mean cumulative effective dose (mSv)* [b]		
	Utility workers		*Contract workers*	*Utility workers*		*Contract workers*
	Plant	*Non-plant*		*Plant*	*Non-plant*	
Maintenance	2300	1000	2000	13	13	19
Operation	400	250	440	13	4	18
Health physics	110	220	710	47	4	71
Supervisory	90	53	140	29	7	25
Engineering	110	150	590	17	7	26
All categories	4960		4000	13		31

[a] Rounded to two significant figures.
[b] To measurably exposed workers.

Table 19
Average cumulative effective doses (mSv) from external radiation to workers at Sellafield [B9]

Follow-up period (years)	*Year of first monitoring*									
	1949-1950	*1953-1954*	*1957-1958*	*1961-1962*	*1965-1966*	*1969-1970*	*1973-1974*	*1977-1978*	*1981-1982*	*1985-1986*
1	2.3	10.1	8.8	5.6	5.1	5	7.6	5.3	3	2.3
2	7.3	24.8	24.4	14.8	15	16.6	23.3	15	7.2	5.8
3	30.8	42.9	43.8	22.4	26.5	31.5	41.3	25.4	12.6	
4	59.5	64	61.7	32.3	40.1	46.1	56.8	35.4	19.3	
5	83.8	81.2	78.9	46.5	53.8	58.2	71	44.4	23.4	
6	110	96.1	94.6	63.6	70.1	73.2	84.4	52.9	29.8	
7	144	114	108.8	82.5	85.7	87	97.9	61.5		
8	179	135	125.2	100	101	97.2	112	69.5		
9	201	150	144.1	116	117	109	125	73.4		
10	220	164	161.3	133	132	120	136	76.1		
11	245	174	180.7	147	142	136	148			
12	266	187	201	160	156	147	157			
13	288	202	219	173	166	156	162			
14	300	218	239	185	176	164	147			
15	319	236	258	196	184	171				
16	335	251	275	207	191	176				
17	359	271	291	215	203	179				
18	379	285	302	229	217	149				
19	404	304	314	238	227					
20	429	317	323	243	228					
21	451	335	332	251	234					
22	468	347	346	259	277					
23	485	363	365	266						
24	502	363	381	280						
25	524	376	387	288						
26	553	395	399	329						
27	569	414	408							
28	587	422	430							
29	622	426	443							
30	632	441	460							
31	665	447								
32	667	462								
33	673	467								
34	686	472								
35	704									
36	721									
37	751									
38	750									

Table 20
Cumulative doses to workers at industrial and research establishments in the United Kingdom [K5]

Distribution basis	*Number of workers (thousands)*	*Collective effective dose (man Sv)*	*Mean cumulative effective dose (mSv)*	*Number of individuals in cumulative effective dose range (thousands)*			
				<10 mSv	*10-50 mSv*	*50-100 mSv*	*>100 mSv*
Distribution by site (employer)							
BNFL	25.6	1805	70.4	10.2	7.46	3.08	4.85
MOD-AWE	10.2	85	8.3	8.6	1.25	0.24	0.15
MOD-DRPS	27.2	381	14.0	20.7	4.64	1.02	0.88
Nuclear Electric	8.2	198	24.1	4.5	2.53	0.7	0.48
UKAEA	23.9	730	30.5	14.9	5.46	1.63	1.91
Total [a]	95.2	3198	33.6	58.9	21.3	6.67	8.27
Distribution by year of birth							
Before 1915	6.40	361	56.4	3.33	1.53	0.57	0.97
1915-1919	3.46	276	79.7	1.47	0.89	0.38	0.72
1920-1924	6.36	437	68.8	2.77	1.71	0.69	1.20
1925-1929	7.30	456	62.4	3.30	1.95	0.83	1.23
1930-1934	7.98	406	50.8	3.86	2.18	0.84	1.10
1935-1939	8.29	309	37.3	4.43	2.30	0.73	0.83
1940-1944	8.97	259	28.9	5.32	2.39	0.61	0.66
1945-1949	11.1	261	23.6	7.09	2.64	0.68	0.67
1950-1954	10.9	211	19.4	7.38	2.34	0.61	0.52
1955-1959	12.7	156	12.3	9.73	2.09	0.53	0.31
1960-1964	9.14	59	6.5	7.75	1.13	0.20	0.06
1965-1969	2.72	7.9	2.9	2.51	0.19	0.01	0.00
After 1970	0.01	0.0	0.1	0.01	0	0	0
Total [a]	95.2	3198	33.6	58.9	21.3	6.67	8.27
Distribution by year in which radiation work began							
1940-1944	0.00	0.0	35.0	0	0.001	0	0
1945-1949	1.64	83.6	50.9	0.76	0.41	0.23	0.25
1950-1954	5.92	664	112	2.05	1.55	0.68	1.64
1955-1959	10.8	752	69.8	4.34	3.02	1.30	2.11
1960-1964	10.6	460	43.3	5.47	2.85	1.00	1.32
1965-1969	8.34	333	39.9	3.72	2.93	0.79	0.90
1970-1974	10.2	363	35.8	4.98	3.28	0.90	1.00
1975-1979	22.5	399	17.7	15.7	4.52	1.31	0.93
1980-1984	17.9	125	7.0	14.9	2.44	0.42	0.12
After 1985	7.39	19.2	2.6	6.98	0.35	0.06	0.00
Total [a]	95.2	3200	33.6	58.9	21.3	6.67	8.27

[a] Minor inconsistencies in totals are due to rounding of values after summation.

Table 21
Worldwide average annual exposures from the commercial nuclear fuel cycle [a]

Practice	*Monitored workers (thousands)*	*Average annual collective effective dose (man Sv)*	*Average annual effective dose to monitored workers (mSv)*	*Distribution ratio* [b]	
				NR_{15} [c]	SR_{15}
1975-1979					
Mining [d,e]	240	1300	5.5	0.37	0.69
Milling [d,e]	12	120	10	0.41	0.76
Enrichment [d]	11	5.3	0.5	0	0
Fuel fabrication	20	36	1.8	0.012	0.38 [h]
Reactor operation	150	600	4.1	0.078 [g]	0.60 [i]
Reprocessing [f]	7.2	53	7.3	0.16	0.29 [f]
Research	120	170	1.4	0.035	0.42
Total	560	2300	4.1	0.20	0.63
1980-1984					
Mining [d,e]	310	1600	5.1	0.30	0.61
Milling [d,e]	23	120	5.1	0.30	0.64
Enrichment [d]	4.3	0.8	0.2	0	0
Fuel fabrication	21	21	1.0	0.002	0.11 [h]
Reactor operation	290	1000	3.6	0.069 [g]	0.52 [i]
Reprocessing [f]	9.4	47	4.9	0.10	0.11 [f]
Research	130	150	1.1	0.021	0.39
Total	800	3000	3.7	0.16	0.55
1985-1989					
Mining [d,e]	260	1100	4.4	0.25	0.52
Milling [d,e]	18	120	6.3	0.18	0.43
Enrichment [d]	5.0	0.4	0.08	0	0
Fuel fabrication	28	22	0.78	0.002	0.019 [h]
Reactor operation	430	1100	2.5	0.033 [g]	0.34 [i]
Reprocessing [f]	12	36	3.0	0.064	0.12 [f]
Research	130	100	0.82	0.011	0.30
Total	880	2500	2.9	0.10	0.42

[a] The data are annual values averaged over the indicated periods.
[b] 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.
[c] This ratio applies to monitored workers.
[d] Also includes uranium obtained or processed for purposes other than the commercial nuclear fuel cycle.
[e] 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 (cf. 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.
[f] Also includes the reprocessing of some fuel from the defence nuclear fuel cycle.
[g] Does not include data for LWGRs, FBRs and HTGRs.
[h] 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.
[i] Does not include data for GCRs, LWGRs, FBRs and HTGRs.

Table 22
Summary of normalized collective effective doses for the fuel cycle based on specific reactor types [a]

Practice	*Normalized collective effective dose [man Sv (GW a)$^{-1}$]*					
	LWRs			*HWRs*	GCRs	
	PWRs	*BWRs*	*All*		*Magnox*	*AGRs*
1975-1979						
Mining [b]	5.7	5.7	5.7	4.7	8.5	5.7
Milling [b]	0.52	0.52	0.52	0.42	0.78	0.52
Enrichment [c]	0.02	0.02	0.02	0	0	0.02
Fuel fabrication	0.69	0.69	0.69	0.20	0.71	0.33
Reactor operation	8.1	18	12	11	7.8	1.1 [e]
Reprocessing	0.7	0.70	0.70		17	0.75
Research [d]	1	1	1	1	1	1
Total without reprocessing	16	26	20	17	19	9.4
Total with reprocessing	17	27	21		36	8.7
1980-1984						
Mining [b]	5.5	5.5	5.5	4.3	8.3	5.5
Milling [b]	0.41	0.41	0.41	0.33	0.61	0.41
Enrichment [c]	0.02	0.02	0.02	0	0	0.02
Fuel fabrication	0.19	0.19	0.19	0.16	0.81	0.31
Reactor operation	8.0	18	11	8.0	8.0	1.1 [e]
Reprocessing	0.75	0.75	0.75		12	0.75
Research [d]	1	1	1	1	1	1
Total without reprocessing	15	25	18	14	19	8.4
Total with reprocessing	16	26	19		31	9.1
1985-1989						
Mining [b]	4.3	4.3	4.3	3.6	6.7	4.3
Milling [b]	0.44	0.44	0.44	0.36	0.66	0.44
Enrichment [c]	0.02	0.02	0.02	0	0	0.02
Fuel fabrication	0.07	0.07	0.07	0.22	1.4	0.45
Reactor operation	4.3	7.9	5.2	6.2	6.7	1.1
Reprocessing	0.65	0.65	0.65		11	0.65
Research [d]	1	1	1	1	1	1
Total without reprocessing	10	14	11	11	16	7.5
Total with reprocessing	11	15	12		27	8.1

[a] The data are annual values averaged over the indicated periods and are, in general, quoted to two significant figures.

[b] 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 (cf. 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.

[c] Probably an overestimate, as the collective doses from which the normalized values were derived contain a contribution from enrichment for purposes other than the commercial nuclear fuel cycle.

[d] This rounded approximate value has been estimated by associating the collective dose received from research carried out in the period 1955-1989 with the sum of the energy generated in the same period plus that likely to be generated by existing reactors over the next 30 years. The value is judged to be an overestimate.

[e] The value for 1985-1989 was assigned in the absence of other data.

Table 23
Exposures to workers from defence activities [a]
Data from UNSCEAR Survey of Occupational Exposures

Country and period	Number of ships [b]	Monitored workers (thousands)	Measurably exposed workers (thousands)	Annual collective effective dose (man Sv)	Annual collective effective dose per ship (man Sv) [b]	Average annual effective dose: Per monitored worker (mSv)	Average annual effective dose: Per measurably exposed worker (mSv)	Distribution ratio: NR_{15}	Distribution ratio: SR_{15}
Weapons fabrication and associated activities									
United Kingdom [c]									
1975-1979 [d]	*Not applicable*	3.14		2.95	*Not applicable*	0.94		0	0
1980-1984		3.71		3.56		0.96		0.0002	0
1985-1989		4.20		2.46		0.59		0	0
United States [c]									
1975-1979	*Not applicable*	17.6	9.31	10.9	*Not applicable*	0.62	1.17		
1980-1984		18.3	8.26	11.7		0.62	1.41		
1985-1989		15.9	7.54	11.9		0.75	1.58		
Total [f]									
1975-1979	*Not applicable*	20.8		13.8	*Not applicable*	0.67			
1980-1984		22.5		15.2		0.68			
1985-1989		20.1		14.4		0.71			
Nuclear ships and their support facilities									
On-board personnel									
United Kingdom [g]									
1975-1979 [d]	15	1.81		5.89	0.39	3.26		0.025	
1980-1984	16	0.89		2.30	0.14	2.57		0.018	
1985-1989	19	0.86		1.44	0.075	1.68		0.011	
United States [h]									
1975-1979	120	20.1		22.9	0.19	1.14		0.017 [i]	
1980-1984	136	26.2		16.3	0.12	0.62			
1985-1989	148	34.1		15.4	0.10	0.45		0.002 [i] 0.001 [i]	
Total [f]									
1975-1979	135	21.9		28.8	0.21	1.31			
1980-1984	153	27.1		18.6	0.12	0.68			
1985-1989	167	34.9		16.8	0.10	0.48			
Shore-based personnel									
United Kingdom [g]									
1975-1979 [d]	15	4.55		20.4	1.4	4.48		0.088	
1980-1984	16	5.54		17.8	1.1	3.21		0.056	
1985-1989	19	5.39		10.2	0.53	1.89		0.021	
United States [h]									
1975-1979	120	15.1		43.0	0.36	2.84		0.096 [i]	
1980-1984	136	19.1		29.5	0.22	1.54		0.027 [i]	
1985-1989	148	22.3		30.2	0.21	1.36		0.029 [i]	
Total [f]									
1975-1979	135	19.7		63.4	0.47	3.22			
1980-1984	153	24.7		47.3	0.31	1.92			
1985-1989	167	27.7		40.4	0.24	1.46			
All personnel									
United Kingdom [g]									
1975-1979 [d]	15	6.36		26.3	1.8	4.13		0.071	
1980-1984	16	6.43		20.1	1.2	3.11		0.050	
1985-1989	19	6.24		11.6	0.61	1.86		0.019	

Table 23 (continued)

Country and period	Number of ships [b]	Monitored workers (thousands)	Measurably exposed workers (thousands)	Annual collective effective dose (man Sv)	Annual collective effective dose per ship (man Sv) [b]	Average annual effective dose		Distribution ratio	
						Per monitored worker (mSv)	Per measurably exposed worker (mSv)	NR_{15}	SR_{15}
United States [h]									
1975-1979	120	35.2		65.9	0.55	1.87		0.051 [i]	
1980-1984	136	45.3		45.8	0.34	1.01		0.012 [i]	
1985-1989	148	56.4		45.6	0.31	0.81		0.012 [i]	
Total [f]									
1975-1979	135	41.6		92.2	0.69	2.22			
1980-1984	153	51.8		65.8	0.43	1.27			
1985-1989	167	62.6		57.3	0.34	0.91			
All defence activities									
United Kingdom [j]									
1975-1979 [d]	*Not*	11.9		35.8	*Not*	3.00		0.04	
1980-1984	*applicable*	12.8		26.3	*applicable*	2.06		0.028	
1985-1989		12.2		14.6		1.19		0.010	
United States									
1975-1979	*Not*	92.5	55.8	101	*Not*	1.09	1.81		
1980-1984	*applicable*	104	61.5	56	*applicable*	0.54	0.91		
1985-1989		115	73.0	69		0.60	0.95		
Total [f]									
1975-1979	*Not*	104		137	*Not*	1.3			
1980-1984	*applicable*	116		82	*applicable*	0.71			
1985-1989		127		84		0.66			

[a] The data are annual values averaged over the indicated periods.
[b] This column applies only for entries under "Nuclear ships and their support facilities".
[c] Data from [D1]. The actual effective doses are typically less than 50% of the tabulated values, which are those measured by the dosimeter.
[d] The value for this period are averages for the year 1979.
[e] 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 each dose interval; subsequently, actual individual doses were used in the summation.
[f] Values derived as the sum or weighted average of the five-year averaged data for the United Kingdom and the United States.
[g] Data from [D1]. The data are reported for on-board and shore personnel. Shore-based personnel may comprise 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.
[h] Data from [N1, M9 and M10]; the data reported for fleet and shipyard personnel are categorized here under "on-board" and "shore based" notwithstanding the lack of direct equivalence between the respective categories.
[i] The values are for the fraction of the workforce receiving annual doses in excess of 10 mSv.
[j] Data from [D1], including exposures from all defence activities.

Table 24
Distribution of cumulative doses from defence activities in the United Kingdom and in the United States

Cumulative effective dose (mSv)	*Percentage of workforce*		
Nuclear weapons programme			
United Kingdom, 1989			
0- 50	96.4		
50-100	2.34		
100-200	0.90		
200-300	0.25		
300-400	0.05		
400-500	0.03		
>500	0		
Number of personnel in 1989 [a]	3843		
Nuclear ships (operation and support)			
United Kingdom, 1989	On board	On shore	Total
0- 50	98.0	83.0	87.4
50-100	1.8	9.2	7.0
100-200	0.2	5.2	3.7
200-300	0.0	1.8	1.3
300-400	0.0	0.57	0.40
400-500	0.0	0.18	0.13
>500	0.0	0.03	0.02
Number of personnel in 1989	1929	4627	6556
United States, 1991			
0- 50	99.67	88.85	
50-100	0.32	6.99	
100-150	<0.01	2.23	
150-200	0	1.12	
200-250	0	0.47	
250-300	0	0.26	
300-500	0	0.08	
>500		<0.01	
Defence workers			
United Kingdom, 1989	Service personnel	Civilian personnel	Total
0- 50	97.3	85.7	89.7
50-100	2.2	7.4	5.6
100-200	0.31	4.4	3.0
200-300	0.03	1.6	1.1
300-400	0.07	0.54	0.37
400-500	0.08	0.25	0.19
>500	0.001	0.04	0.03

[a] Includes about 95% of the workforce involved with the nuclear weapons programme.

Table 25
Cumulative doses in dose registries for defence workers in the United Kingdom

Cumulative effective dose (mSv)	*Percentage of workforce*											
	Central Index on Dose Information [a]					*National Registry on Radiation Workers* [b]						
	Weapons programme [c]		*Other defence* [d]		*All defence employees*	*All doses* [e]			*Doses to age 30 years* [f]			
	Employees	*Contract workers*	*Employees*	*Contract workers*		*Weapons programme* [c]	*Other defence activities* [d]	*All defence activities*	*Weapons programme* [c]	*Other defence activities* [d]	All defence activities	
<1	19.9	21.6	28.8	9.6	20.0	18.7	37.7	33.1	61.8	61.0	61.2	
1-5	24.9	28.3	20.8	12.7	20.9	33.0	25.5	27.3	21.4	19.9	20.2	
5-10	12.7	19.3	13.0	10.7	12.6	16.7	11.5	12.8	8.4	7.5	7.7	
10-20	15.7	18.6	13.1	11.7	14.1	14.9	9.9	11.1	5.3	5.5	5.4	
20-50	16.0	9.8	14.7	20.1	16.4	11.9	8.4	9.2	2.4	3.8	3.5	
50-100	5.7	2.3	6.3	16.5	8.3	3.2	3.8	3.6	0.50	1.4	1.2	
100-200	3.9	0	2.5	11.8	5.2	1.2	2.2	1.9	0.18	0.65	0.53	
200-300	0.84	0	0.52	4.5	1.6	0.27	0.67	0.57	0.05	0.14	0.12	
300-400	0.28	0	0.16	1.7	0.58	0.08	0.26	0.22	0	0.02	0.01	
400-600	0.03	0	0.12	0.74	0.22	0.02	0.12	0.09	0.01	0.01	0.01	
>600	0.03	0	0	0	0.01	0.01	0.03	0.03	0.01	0.02	0.01	
Number of workers	3913	388	2490	2157	8948	10278	32523	42810	10278	32523	42810	
Average cumulative dose (mSv)	21.8	9.4	18.3	58.1	29.0	13.0	14.5	14.1	3.5	5.3	4.9	

[a] Data from the Central Index on Dose Information (CIDI) are for classified radiation workers only, including employees and contractors of the Ministry of Defence. External and internal doses are included.
[b] Data from the National Registry on Radiation Workers are for classified and non-classified workers up to 1986, including only employees of the Ministry of Defence and not contractor workers. External and internal doses are included.
[c] Data strictly for the Atomic Weapons Establishment only, but can be assumed to be representative of the weapons programme as a whole.
[d] Data are for those monitored by the Defence Radiological Protection Service. They comprise all defence employees and contractors apart from those of the Atomic Weapons Establishment. Most of these exposures are associated with the naval nuclear propulsion programme.
[e] The percentages are for the total cumulative dose received by individual workers on the National Registry on Radiation Workers.
[f] The percentages are for the cumulative dose received by individual workers up to the age of 30 years.

Table 26
Exposures to workers from industrial uses of radiation (excluding the commercial nuclear fuel cycle and defence activities) [a]
Data from UNSCEAR Survey of Occupational Exposures unless otherwise indicated

Country and period	Monitored workers (thousands)	Measurably exposed workers (thousands)	Annual collective effective dose (man Sv)	Average annual effective dose		Distribution ratio	
				Per monitored worker (mSv)	Per measurably exposed worker (mSv)	NR_{15} [b]	SR_{15}
Industrial radiography							
Argentina							
1985-1989	0.046	0.01	0.027	0.59	2.7	0	0
Australia [c,d]							
1985-1989	0.40	0.26	0.40	1.01	1.52	0.007	0.11
Brazil							
1985-1989				3.3	14.5		
Canada							
1975-1979	1.07	0.71	4.33	4.05	6.08	0.077	0.51
1980-1984	1.46	0.76	4.88	3.35	6.41	0.056	0.50
1985-1989	1.43	0.84	6.47	4.51	7.75	0.093	0.57
China (Taiwan Province)							
1985-1989	1.01		1.53	1.52			
Czechoslovakia							
1975-1979	0.54		1.24	2.31		0.027	0.31
1980-1984	1.03		2.19	2.12		0.016	0.16
1985-1989	1.32		2.15			0.011	0.14
Denmark							
1975-1979	0.24		0.23	0.98		0.003	0.080
1980-1984	0.33		0.43	1.33		0.009	0.12
1985-1989	0.41		0.48	1.19		0.004	0.076
Finland							
1980-1984		0.03	0.05		1.51		0
1985-1989		0.06	0.11		1.65		0
France [e]							
1975-1979	1.28		1.47	1.15			0.027
1985-1989	1.6	0.09	0.28	0.18	3.11	0.002	
German Dem. Rep.							
1980-1984	2.09	0.43	0.83	0.40	1.93	0.002	0.17
1985-1989	2.15	0.32	0.39	0.18	1.23	0.002	0.22
Germany, Fed. Rep. of							
1985-1989	4.67	1.61	7.10	1.52	4.41	0.023	0.33
Hungary							
1975-1979	1.13	0.41	2.54	2.25	6.13	0.029	0.40
1980-1984	1.24	0.39	1.47	1.19	3.79	0.012	0.22
1985-1989	1.16	0.37	1.15	0.99	3.14	0.005	0.13
India							
1980-1984	2.93	1.39	9.0	3.07	6.50	0.055	0.55
1985-1989	4.23	2.16	13.2	3.12	6.10	0.058	0.54
Indonesia							
1980-1984	0.14	0.02	0.22	1.53	10.8	0.033	0.45
1985-1989	0.43	0.03	0.40	0.95	14.9	0.059	0.10
Ireland							
1980-1984	0.07	0.04	0.05	0.75	1.39	0	0
1985-1989	0.05	0.03	0.06	1.41	2.57	0.010	0.15

Table 26 (continued)

Country and period	Monitored workers (thousands)	Measurably exposed workers (thousands)	Annual collective effective dose (man Sv)	Average annual effective dose		Distribution ratio	
				Per monitored worker (mSv)	Per measurably exposed worker (mSv)	NR_{15} [b]	SR_{15}
Japan							
1980-1984	3.31	1.58	5.67	1.71	3.59	0.015	
1985-1989	2.83	1.08	3.35	1.19	3.09	0.006	
Mexico							
1985-1989	0.82	0.49	5.10	6.23	10.5	0.102	0.67
Netherlands [f]							
1980-1984	0.97		0.34	0.35		0.002	0.13
1985-1989	1.02		0.48	0.47		0.004	0.20
New Zealand [M2]							
1980-1984	0.15		0.35	2.33			
Norway							
1980-1984	0.80	0.44	0.79	0.99	1.81	0.001	0.038
1985-1989	0.82	0.40	0.62	0.76	1.56	0.003	0.10
South Africa							
1975-1979	0.57	0.31	0.11	0.19	0.35	0	0
1980-1984	0.75	0.45	2.38	3.18	5.30	0.052	0.44
1985-1989	0.72	0.32	1.68	2.33	5.29	0.033	0.36
Spain							
1985-1989	0.82	0.66	1.23	1.50	1.87	0.018	0.32
Sweden							
1975-1979	0.77	0.19	0.49	0.63	2.56	0.005	0.16
1980-1984	0.66	0.17	0.38	0.57	2.27	0.002	0.059
1985-1989	0.64	0.25	0.28	0.43	1.12	0.002	0.15
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			
United Kingdom [g]							
1980-1984	1.82		3.60	1.98		0.023	0.43
1985-1989	4.82	4.08	5.67	1.18	1.39	0.009	
United States [h]							
1975-1979	17		50	2.94			
1980-1984	27		80	2.96			
1985-1989	23	12	39	1.70	3.25		
Total of reported data [i]							
1975-1979	24.0		89.5	3.74		0.037	0.39
1980-1984	42.1		125	2.98		0.028	0.42
1985-1989	49.9		98.7	1.98		0.026	0.44
World [j]							
1975-1979	72		190	2.61			
1980-1984	116		230	1.98			
1985-1989	108		160	1.44			
Radiography carried out at fixed locations [k]							
Netherlands							
1980-1984	0.49		0.04	0.07			
1985-1989	0.54		0.06	0.11			
United Kingdom [K3, H2]							
1980-1984	1.29		2.00	1.55		0.026	
United States [l]							
1975-1979	2.07		2.80	1.35		0.009	0.42
1980-1984	3.54		3.90	1.10		0.007	0.17
1985-1989	1.85		0.67	0.36		0.001	0.19

Table 26 (continued)

Country and period	Monitored workers (thousands)	Measurably exposed workers (thousands)	Annual collective effective dose (man Sv)	Average annual effective dose: Per monitored worker (mSv)	Average annual effective dose: Per measurably exposed worker (mSv)	Distribution ratio: NR_{15} [b]	Distribution ratio: SR_{15}
Total of reported data [j]							
1975-1979	2.07		2.80	1.35		0.009	0.42
1980-1984	3.54		3.90	1.10		0.007	0.17
1985-1989	1.85		0.67	0.36		0.001	0.19
Radiography carried out with mobile units [k]							
Netherlands							
1980-1984	0.28		0.24	0.84			
1985-1989	0.30		0.34	1.17			
United Kingdom [K3, H2]							
1980-1984	0.57		0.99	1.75		0.015	
United States [m]							
1975-1979	10.4	5.78	30.9	2.97	5.34	0.033	0.50
1980-1984	7.71	4.93	25.1	3.26	5.10	0.042	0.49
1985-1989	6.13	4.30	20.0	3.27	4.66	0.043	0.44
Total of reported data [j]							
1975-1979	10.4		30.9	2.97		0.033	0.50
1980-1984	8.56		26.4	3.08		0.041	0.47
1985-1989	6.42		20.4	3.17		0.043	0.44
Luminizing industries [k]							
France [P2]							
1975-1979	0.071		0.375	5.30			0.66
1980-1984	0.044		0.242	5.52		0.14	0.55
1985-1989	0.027		0.182	6.84		0.17	0.52
India [n]							
1980-1984	0.067	0.028	0.077	1.16	2.78	0.011	0.16
1985-1989	0.151	0.056	0.190	1.26	3.37	0.021	0.54
Switzerland [S13]							
1975-1979	0.206		2.31	11.2		0.25	0.53
1980-1984	0.130		1.02	7.82		0.14	0.39
1985-1989	0.158		0.68	4.31		0.039	0.18
United Kingdom (paint) [U3]							
1975-1979	0.093		0.40	4.32			0.35
United Kingdom (tritium) [o]							
1975-1979	0.25		1.46	5.89		0.12	0.65
1980-1984	0.33		1.10	3.33		0.057	0.40
Total of reported data [j]							
1975-1979	0.51		3.77	7.44		0.18	0.58
1980-1984	0.27		1.34	5.01		0.081	0.37
1985-1989	0.54		1.45	2.71		0.026	0.31
Radioisotope production and distribution							
Argentina							
1975-1979	0.17		0.67	4.05		0	0
1980-1984	0.22		0.45	2.10		0	0
1985-1989	0.18		0.44	2.47		0	0
Canada [p]							
1975-1979	0.046	0.032	0.12	2.67	3.84	0.017	0.14
1980-1984	0.033	0.027	0.19	5.83	7.28	0.090	0.41
1985-1989	0.295	0.162	0.48	1.61	2.94	0.014	0.18

Table 26 (continued)

Country and period	*Monitored workers (thousands)*	*Measurably exposed workers (thousands)*	*Annual collective effective dose (man Sv)*	*Average annual effective dose*		*Distribution ratio*	
				Per monitored worker (mSv)	*Per measurably exposed worker (mSv)*	NR_{15} [b]	SR_{15}
Czechoslovakia							
1975-1979	0.18		0.50	2.76		0.018	0.19
1980-1984	0.33		0.60	1.80		0.022	0.30
1985-1989	0.40		0.81	2.05		0.035	0.42
Finland [g]							
1975-1979		0.003	0.011		4.23		0
1980-1984		0.005	0.020		3.92		0
1985-1989		0.013	0.052		4.10		0
Hungary							
1975-1979	0.21	0.079	0.27	1.33	3.49	0.014	0.21
1980-1984	0.25	0.090	0.30	1.18	3.35	0.005	0.097
1985-1989	0.24	0.088	0.32	1.31	3.56	0.008	0.16
India							
1980-1984	0.40	0.31	0.67	1.69	2.20	0.010	0.17
1985-1989	0.51	0.35	0.71	1.39	2.02	0.008	0.14
Indonesia							
1975-1979	0.025		0.11	4.34			
1980-1984	0.034	0.030	0.060	1.76	2.03	0	0
1985-1989	0.046	0.040	0.083	1.81	2.10	0	0
Netherlands [f]							
1985-1989	0.18		0.87	4.97		0.040	0.13
Republic of Korea							
1975-1979	0.023	0.020	0.12	5.22	6.00	0.095	0.32
1980-1984	0.020	0.020	0.15	7.43	7.65	0.34	0.64
1985-1989	0.016	0.013	0.086	5.38	6.52	0.063	0.17
South Africa							
1975-1979	0.019		0.16	8.74		0.23	0.71
1980-1984	0.029		0.16	5.27		0.10	0.57
1985-1989	0.031		0.18	5.75		0.12	0.52
United Kingdom [r]							
1975-1979	0.97		6.39	6.59		0.14	
1980-1984	1.26		4.82	3.84		0.067	
1985-1989	1.72		4.63	2.70		0.029	
United States							
1975-1979	20		40	2.00			
1980-1984	29		30	1.03			
1985-1989	30	17	25	0.83	1.47		
Total of reported data [i]							
1975-1979	21.6		48.3	2.23		0.095	0.18
1980-1984	31.5		37.3	1.18		0.045	0.23
1985-1989	33.2		32.7	0.98		0.025	0.23
World [j]							
1975-1979	57		130	2.25			
1980-1984	82		100	1.26			
1985-1989	88		98	1.12			
Well logging [k]							
Canada							
1975-1979	0.45	0.21	0.52	1.16	2.43	0.008	0.17
1980-1984	1.01	0.58	1.28	1.27	2.21	0.005	0.11
1985-1989	1.11	0.74	1.37	1.24	1.85	0.003	0.051
Czechoslovakia [s]							
1975-1979	0.057		0.058	1.02		0	0
1980-1984	0.092		0.15	1.60		0.002	0.032
1985-1989	0.114		0.20	1.72		0.002	0.016

Table 26 (continued)

Country and period	Monitored workers (thousands)	Measurably exposed workers (thousands)	Annual collective effective dose (man Sv)	Average annual effective dose		Distribution ratio	
				Per monitored worker (mSv)	Per measurably exposed worker (mSv)	NR_{15} [b]	SR_{15}
India [l]							
1980-1984	0.19	0.041	0.072	0.38	1.75	0.006	0.39
1985-1989	0.64	0.30	0.38	0.54	1.25	0.002	0.086
Indonesia							
1980-1984	0.14	0.038	0.12	0.82	3.07	0	0
1985-1989	0.56	0.45	0.84	1.51	1.89	0	0
Mexico							
1985-1989	0.36	0.013	0.004	0.012	0.32	0	0
South Africa							
1975-1979	0.043	0.012	0.000	0.007	0.025		
1980-1984	0.040	0.017	0.064	1.61	3.76		
1985-1989	0.035	0.012	0.053	1.49	4.55		
United States [u]							
1975-1979	7.6		10.3	1.36			0.3
Total of reported data [v]							
1975-1979				1.32		0.007	0.27
1980-1984				1.17		0.004	0.10
1985-1989				1.07		0.002	0.039
Tertiary education and research institutes							
Australia [c d]							
1975-1979	0.55		0.055	0.10			
1985-1989	2.22	0.94	0.069	0.03	0.07	0	0
Canada [w]							
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
China (Taiwan Province)							
1985-1989	0.71		0.04	0.056			
Czechoslovakia							
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
Finland [z]							
1980-1984	0.95	0.023	0.038	0.040	1.63	0	0.062
1985-1989	1.18	0.032	0.053	0.045	1.68	0.008	0.11
France [P2]							
1985-1989	3.8	0.09	0.20	0.053	2.22	0.001	
German Dem. Rep. [y]							
1975-1979	2.71		0.034	0.013			
1980-1984	3.07		0.056	0.018			
1985-1989	3.25	0.30	0.16	0.048	0.52		
Germany, Fed. Rep. of [r]							
1985-1989	21.1	1.05	1.53	0.072	1.46	0.0004	0.17
Hungary [aa]							
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	0
1985-1989	0.21	0.005	0.009	0.044	2.02	0	0
India [bb]							
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

Table 26 (continued)

Country and period	*Monitored workers (thousands)*	*Measurably exposed workers (thousands)*	*Annual collective effective dose (man Sv)*	*Average annual effective dose*		*Distribution ratio*	
				Per monitored worker (mSv)	*Per measurably exposed worker (mSv)*	NR_{15} [b]	SR_{15}
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	0.0003	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	
Norway [cc]							
1980-1984	0.42	0.025	0.014	0.032	0.55	0	0
1985-1989	0.45	0.029	0.026	0.057	0.90	0.001	0.48
Portugal							
1985-1989	0.78	0.37	0.33	0.42	0.88		
South Africa							
1975-1979	0.23	0.042	0.002	0.007	0.04	0	0
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 -	0.10
Switzerland [dd]							
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	
United Kingdom [l]							
1980-1984	12.5		1.3	0.10		0	0
1985-1989	1.17	0.49	0.38	0.32	0.78	0.002	
United States [m]							
1975-1979	25		18	0.72			
1980-1984	26		15	0.58			
1985-1989	17		6	0.35	0.86		
Total of reported data [i]							
1975-1979	38.6		23.5	0.61		0.004	0.19
1980-1984	66.0		20.4	0.31		0.0007	0.11
1985-1989	85.7		13.6	0.16		0.0004	0.072
World [j]							
1975-1979	140		74	0.55			
1980-1984	180		43	0.24			
1985-1989	160		22	0.14			
Accelerators [k]							
Canada							
1975-1979	0.58	0.19	0.17	0.30	0.91	0.0003	0.098
1980-1984	0.88	0.23	0.40	0.45	1.76	0.0009	0.043
1985-1989	1.00	0.53	1.06	1.06	2.00	0.0038	0.067
Finland							
1980-1984		0.008	0.010		1.23		0
1985-1989		0.007	0.013		1.75		0
Netherlands							
1980-1984	0.18	0.009	0.006	0.03	0.67	0	0
1985-1989	0.16	0.010	0.004	0.03	0.46	0	0
South Africa							
1975-1979	0.07	0.03	0.030	0.46	1.00	0	0
1980-1984	0.10	0.04	0.27	2.72	6.59	0.046	0.55
1985-1989	0.22	0.07	0.34	1.56	4.76	0.035	0.61

Table 26 (continued)

Country and period	Monitored workers (thousands)	Measurably exposed workers (thousands)	Annual collective effective dose (man Sv)	Average annual effective dose: Per monitored worker (mSv)	Average annual effective dose: Per measurably exposed worker (mSv)	Distribution ratio: NR_{15} [b]	Distribution ratio: SR_{15}
United Kingdom [H2] [ee]							
1985-1989	0.50		0.25	0.50		0	0
United States [M1] [ff]							
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		
Total of reported data [i]							
1975-1979	4.50		7.38	1.62		0.0004	0.12
1980-1984	4.93		3.73	0.76		0.005	0.26
1985-1989	5.72		3.52	0.62		0.008	0.19
[r] All industrial activities (excluding nuclear fuel cycle and defence activities)							
Argentina							
1985-1989	0.066	0.031	0.085	1.29	2.74	0.030	0.61
Australia [c d]							
1975-1979	2.21		0.92	0.41			
1985-1989	7.10	3.33	0.78	0.11	0.23	0.001	0.091
Brazil [D2]							
1985-1989	15	3.1	24	1.6	7.69		
Canada							
1975-1979	8.06	3.60	13.2	1.63	3.66	0.022	0.42
1980-1984	11.0	4.36	14.4	1.31	3.30	0.016	0.34
1985-1989	10.7	4.70	16.2	1.52	3.45	0.023	0.39
China (Taiwan Province)							
1980-1984	2.42		1.91	0.79			
1985-1989	3.04		1.97	0.65			
Czechoslovakia							
1975-1979	1.65		2.26	1.38		0.011	0.23
1980-1984	2.92		3.77	1.29		0.010	0.18
1985-1989	3.62		3.77	1.04		0.010	0.21
Denmark							
1975-1979	0.46		0.32	0.68		0.002	0.058
1980-1984	0.64		0.49	0.76		0.005	0.11
1985-1989	0.80		0.52	0.65		0.002	0.071
Finland [gg hh]							
1975-1979	0.67	0.05	0.14	0.21	2.97		0.20
1980-1984	2.09	0.15	0.26	0.12	1.75	0.0000	0.046
1985-1989	2.36	0.17	0.32	0.14	1.94	0.0004	0.063
France [P2]							
1985-1989	9.90		24.0	2.42			
Germany, Fed. Rep. of							
1985-1989	58.6	14.7	25.6	0.44	1.74	0.008	0.29
Hungary [ii]							
1975-1979	3.26	0.58	3.01	0.92	5.14	0.011	0.36
1980-1984	3.36	0.56	1.93	0.58	3.47	0.005	0.19
1985-1989	3.26	0.53	1.57	0.48	2.97	0.003	0.12
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	0.0003	0.089

Table 26 (continued)

Country and period	Monitored workers (thousands)	Measurably exposed workers (thousands)	Annual collective effective dose (man Sv)	Average annual effective dose: Per monitored worker (mSv)	Average annual effective dose: Per measurably exposed worker (mSv)	Distribution ratio: NR_{15} [b]	Distribution ratio: SR_{15}
Italy [ii]							
1985-1989	1.98	0.44	0.87	0.44	1.97	0.004	0.35
Japan							
1975-1979	27.6	3.93	8.93	0.32	2.27	0.008	
1980-1984	29.0	4.06	11.0	0.38	2.70	0.005	
1985-1989	32.0	3.06	8.48	0.27	2.77	0.002	
Mexico							
1985-1989	1.63	0.51	5.23	3.21	10.2	0.047	0.66
Netherlands							
1980-1984	1.71		0.63	0.37		0.005	0.34
1985-1989	2.27		0.88	0.39		0	0.15
New Zealand [M2]							
1980-1984	0.28		0.43	1.50			
Norway [kk]							
1980-1984	1.21	0.51	0.85	0.70	1.67	0.002	0.042
1985-1989	1.44	0.51	0.68	0.47	1.35	0.002	0.094
Portugal [C1]							
1985-1989	0.63	0.52	0.18	0.28	0.34		
South Africa							
1975-1979	2.01	0.79	0.21	0.11	0.27	0	0.046
1980-1984	2.90	1.18	6.11	2.11	5.17	0.026	0.41
1985-1989	2.37	0.55	5.71	2.41	10.5	0.004	0.69
Spain							
1985-1989	3.02	2.49	3.98	1.32	1.60	0.009	0.018
Switzerland							
1975-1979	11.7		10.2	0.87		0.010	0.31
1980-1984	12.9		5.92	0.46		0.003	0.14
1985-1989	13.6		4.08	0.30		0.001	0.081
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	18.8	15.1	21.0	1.12	1.39	0.008	
United States [ll]							
1975-1979	202		290	1.44			
1980-1984	305		380	1.25			
1985-1989	274	101	150	0.55	1.49		
Total of reported data [i]							
1975-1979	240		445	1.81		0.014	0.36
1980-1984	386		552	1.43		0.008	0.29
1985-1989	423		343	0.81		0.007	0.34
World [j]							
1975-1979	530	290	870	1.64	3.0	0.010	0.35
1980-1984	690	300	940	1.36	3.2	0.007	0.28
1985-1989	560	250	510	0.90	2.0	0.009	0.31

[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 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] Data also from [M7] and [S6]; numbers of workers and the collective doses reported in questionnaire for about 70% of the exposed workforce have been extrapolated for entire country.

Table 26 (continued)

[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] Data from [U3] for 1975-1979 and from [P2] for 1985-1989.

[f] The reported data (covering about 80% of the workforce) have been scaled to represent the whole country.

[g] Data for 1980-1984 from [K3] and [H2] 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 from [H7] and [B7] are for classified workers only.

[h] Data from [E1, E2 and E3]; data are for 1975, 1980 and 1985 but assumed here to be representative of the respective five-year periods.

[i] 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 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 summated number of workers and collective doses.

[j] The estimates are extrapolations of regional values based on the gross national product (GNP); because of insufficient data, the estimates of NR_{15} and SR_{15} are averages of reported data, but these may be considered representative for worldwide exposure.

[k] Insufficient data are available for these categories to enable a reliable estimate of worldwide exposures.

[l] Data for licencees of the Nuclear Regulatory Commission only.

[m] Data are for licensees of the United States Nuclear Regulatory Commission only.

[n] The doses include exposures from tritium intake and external radiation from promethium-147.

[o] Data for 1980-1984 from [H1] and [H2]. Data for 1985-1989 from [H7] and [B7] include only classified workers.

[p] Before 1989 radioisotope production was undertaken by Atomic Energy of Canada Limited, and separate statistics for 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.

[q] Internal exposure included after 1986; it amounted to about 50%.

[r] Internal exposure included after 1984; its contribution is small.

[s] For 1980-1989, neutron exposure contributed 30%-60% of the total. About one third of the workforce is employed underground and received an internal dose from radon etc, additional to the doses tabulated, in the range of about 5 to 10 mSv a^{-1}.

[t] Neutrons contribute about 15%-25% to the reported doses.

[u] Data are for licensees of the United States Department of Energy only. The effective doses include a neutron component.

[v] Data are only presented for quantities that are averages of the reported data rather than their sums. Summed data would be potentially misleading because of the main contribution that would be made by the data for the United States, for which data for only one period are available. The data should be interpreted with care. In particular, the countries included in the summation for the reporting periods may not be the same.

[w] Data are mainly from universities but exclude exposures at accelerators and in teaching establishments where little research is undertaken.

[x] Includes all research institutes except research reactors and accelerators. No data are available on exposures in tertiary education.

[y] 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.

[z] Data include exposures arising in research and training in natural sciences and technology, including research centres.

[aa] Includes technological education only (i.e. not medicine, science, philosophy etc.).

[bb] Includes data from education and research institutes.

[cc] Data are solely for the Univesity of Oslo.

[dd] Data from [O1]; they may include some data on research for the nuclear fuel cycle.

[ee] Data include exposures at the Science and Engineering (SERC) Laboratories at Chilton and Daresbury.

[ff] Data are for accelerators of the United States Department of Energy. Before 1987 collective doses were evaluated as the sum of the products of the number of workers and the mean dose in each dose interval; subsequently, actual individual doses were used in the summation.

[gg] Includes exposures of workers at the research reactor and in research establishments, including tertiary education.

[hh] Reported data for 1975-1979 contained only estimates of the number of exposed workers; the number of monitored workers was estimated assuming the ratio of exposed to monitored workers in the subsequent period.

[ii] Data do not include exposures for workers in the luminizing industry, in well logging and at accelerators.

[jj] The reported number of workers is small compared with numbers in comparable industrialized countries, which suggests that the data are incomplete.

[kk] Educational establishments not included.

[ll] Data from [E1, E2 and E3]. The data are specifically for the years 1975, 1980 and 1985; they are assumed here to be representative, respectively, of the periods 1975-1979, 1980-1984 and 1985-1989.

Table 27
Percentage of workers in industrial radiography receiving annual effective doses in excess of 50 mSv and the percentage of the collective dose arising from doses above that level
Data from UNSCEAR Survey of Occupational Exposures unless otherwise indicated

Country	*Percentage of workers receiving annual effective dose >50 mSv (NR_{50} × 100)*			*Percentage of collective dose from annual individual doses >50 mSv (SR_{50} × 100)*		
	1975-1979	*1980-1984*	*1985-1989*	*1975-1979*	*1980-1984*	*1985-1989*
Canada	0.5	0.5	0.6	7.3	11	8.2
China (Taiwan Province)			0.7			26
Germany, Fed. Rep. of			0.1			2.4
India		0.5	0.4		13	11
Ireland		0	0		0	0
Japan		0.2	0			
Netherlands		0	0		0	2.8
South Africa		0.3	0		8.5	7.0
United Kingdom [a]		0.13	0.11			
United States [b]						
Fixed locations	0	0	0	5.6	2.1	1.4
Mobile equipment	0.1	0	0	5.2	3.3	2.5
Weighted average [c]	0.10	0.14	0.17	5.4	6.1	6.2

[a] Data from [H1, H2, K3, K4]; those for 1980-1984 are averages over the years 1980 and 1982 and those for 1985-1989 are averages over the years 1986-1987. Data are for radiographers whose dose records are held within the Dosemeter Issue and Record Keeping (DIRK) service of the National Radiological Protection Board (NRPB).

[b] Data for licensees of the United States Nuclear Regulatory Commission only.

[c] Weighted according to the average number of workers or collective dose, as appropriate, in each country in each five-year period.

Table 28
Contribution of different regions to the worldwide exposure from all industrial uses of radiation (excluding the nuclear fuel cycle and defence activities) [a]

Country/region	*Monitored workers* (thousands)	*Average annual collective effective dose* (man Sv)	*Average annual individual dose to monitored workers* (mSv)	*Collective effective dose per unit GNP* [b] (man Sv per 10^{12} $US)	*Collective effective dose per unit population* (man Sv per 10^{9})
1975-1979					
East and south-east Asia [c]					
Eastern Europe [d]	17	176	10	150	440
Latin America					
OECD except United States [e]	210	240	1.1	79	430
United States	200	290	1.4	150	1300
Remainder [f]	100	170	1.7	120	55
Total	530	870	1.6	120	200
1980-1984					
East and south-east Asia [c]	12	9	0.79	20	23
Eastern Europe [d]	20	150	7.9	68	370
Latin America					
OECD except United States [e]	240	240	0.99	49	420
United States	310	380	1.3	110	1600
Remainder [f]	110	160	1.4	73	48
Total	690	940	1.4	72	190
1985-1989					
East and south-east Asia [c]	10	7	0.65	13	15
Eastern Europe [d]	26	140	5.6	41	330
Latin America	24	43	1.8	52	95
OECD except United States [e]	180	130	0.69	16	220
United States	270	150	0.55	31	590
Remainder [f]	41	35	0.85	26	11
Total	560	510	0.9	26	94

[a] The data are annual values averaged over the respective five-year periods and are, in general, quoted to two significant figures.
[b] The normalized collective doses per unit GNP for the three five-year periods are expressed, respectively, in terms of 1977, 1983 and 1989 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 members of the Organization for Economic 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.

Table 29
Cumulative doses received by industrial radiographers in Hungary
[S8]

Duration of employment (years)	*Number of workers*	*Average cumulative effective dose (mSv)*	*Average annual effective dose (mSv)*	*Percentage of workers with cumulative effective doses above specified values*			
				>50 mSv	*>100 mSv*	*>150 mSv*	*>200 mSv*
5	69	14.0	2.8	0	0	0	0
6	72	26.5	4.4	11.1	1.4	0	0
7	44	34.6	4.9	15.9	2.3	0	0
8	44	31.5	3.9	18.2	0	0	0
9	38	37.4	4.2	18.4	5.3	0	0
10	41	44.1	4.4	29.3	4.9	2.4	0
11	32	54.1	4.9	28.1	9.4	6.3	3.1
12	30	60.3	5.0	53.3	16.7	0	0
13	21	66.6	5.6	52.4	14.3	4.8	0
14	26	102.9	7.4	88.5	42.3	7.7	3.8
15	27	102.7	6.8	96.3	44.4	11.1	3.7

Table 30
Summary of worldwide exposures from the industrial uses of radiation (excluding nuclear fuel cycle and defence activities) [a]

Practice	*Monitored workers [b] (thousands)*	*Average annual collective effective dose [c] (man Sv)*	*Average annual individual dose to monitored workers (mSv)*	NR_{15} [d]	SR_{15} [d]
1975-1979					
Industrial radiography	72 (14%)	190 (22%)	2.6	0.037	0.39
Isotope production and distribution	57 (11%)	130 (15%)	2.3	0.095	0.18
Tertiary education and research institutes	140 (25%)	74 (8%)	0.55	0.004	0.19
Other [e]	270 (50%)	480 (55%)	1.8		
All industry	530	870	1.6	0.01	0.35
1980-1984					
Industrial radiography	120 (17%)	230 (24%)	2.0	0.028	0.42
Isotope production and distribution	82 (12%)	100 (11%)	1.3	0.045	0.23
Tertiary education and research institutes	180 (26%)	43 (5%)	0.24	0.001	0.11
Other [e]	310 (45%)	570 (60%)	1.8	0.0007	
All industry	690	940	1.4	0.007	0.29
1985-1989					
Industrial radiography	110 (19%)	160 (31%)	1.4	0.026	0.44
Isotope production and distribution	88 (16%)	98 (19%)	1.1	0.025	0.23
Tertiary education and research institutes	160 (29%)	22 (4%)	0.14	0.0004	0.07
Other [e]	200 (36%)	230 (46%)	1.1		
All industry	560	510	0.90	0.009	0.31

[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 contribution of that practice to the total number of monitored workers in industry.
[c] The numbers in parentheses are the percentage contribution of that practice to the collective dose from all industrial uses of radiation.
[d] The values of NR_{15} and SR_{15} should only be regarded as indicative of worldwide experience. Reported data on these ratios were far fewer than for other quantities of interest (e.g. collective dose, monitored workers etc.) and were insufficient to form the basis for a more reliable and representative estimate of worldwide levels.
[e] Estimated from the "all industrial activities" data in Table 26 by subtracting the contributions from the three specified practices.

Table 31
Dose monitoring and recording procedures for occupational exposures in medicine

Country	*Minimum detectable level (MDL) or recording level*	*Dose recorded when less than MDL*	*Location of dosimeter (below or above apron)*	*Dose recorded for lost dosimeters*	*Recorded dose (direct measurement or corrected)*	*Multiple entries for the same individual*
Australia	0.01 mSv (x rays) 0.07 mSv (gamma rays)	0	Below	0	Corrected	No
Brazil	0.2 mSv [a]	0	Below	Monthly average		Yes
China	0.03 mSv	0.01 mSv	Above	Estimated		No
China (Taiwan Province)	0.03	0	Below	0		Yes (before 1986) No (after 1986)
Denmark	0.1 mSv	0	Below	0	Direct	Yes
Finland	1.5 mSv (1975-1979) 0.5 mSv (1980-1988) 0.3 mSv (1989-1990)	0	Above	0	Direct [b]	No
German Dem. Rep.	0.2 mSv	0	Above	Average of last 12 months		Yes
Germany, Fed. Rep. of	0.4 mSv (before 1979) 0.1 mSv (after 1979)	0	Below	Determined by controlling authorities	Direct	
India	0.05 mSv (x rays) 0.10 mSv (gamma rays)	0	Above (1975-1988) Below (1989-1990)	Average during the year	Corrected [c]	No
Ireland	0.1 or 0.15 mSv [d]	0	Below	0	Direct	No
Mexico	0.01 mSv	0		4.16 mSv	Direct	Yes
Spain	0.1 mSv	0	Below	Area, other dosimeter or 4 mSv	Direct	No
Sweden	0.1 mSv	0	Below	0	Direct	No
Switzerland	0.1 mSv	0	Below	0 for those exposed to low doses; otherwise based on average dose	Direct	Yes (before 1990) No (after 1990)

[a] Recording level.
[b] Analyses have indicated that recorded doses are overestimates by a factor in the range of 3-30 for diagnostic radiography, which contributes about 60% of the reported doses.
[c] For diagnostic x rays, a factor of 0.5 is used to convert measured quantity to effective dose.
[d] 0.1 mSv for dental and diagnostic radiography and veterinary practice; 0.15 mSv for nuclear medicine and radiotherapy.

Table 32
Exposures to workers from medical uses of radiation
Data from UNSCEAR Survey of Occupational Exposures unless otherwise indicated

Country and period [a]	Examinations (millions)	Monitored workers (thousands)	Measurably exposed workers (thousands)	Annual collective effective dose (man Sv)	Average annual effective dose		Distribution ratio	
					Per monitored worker (mSv)	Per measurably exposed worker (mSv)	NR_{15} [b]	SR_{15}
Diagnostic radiography								
Argentina								
1985-1989		2.20	0.83	2.89	1.31	3.46	0.016	0.56
Australia [c d]								
1975-1979	6.1	3.22		1.70	0.53			
1980-1984	7.6							
1985-1989	9.2	6.21	4.42	0.37	0.059	0.083	0	0
Brazil								
1985-1989	15	3.93	1.01	2.99	0.76	2.97	0.009	0.34
Canada								
1975-1979		8.4	4.5	3.23	0.38	0.72	0.0009	0.065
1980-1984		9.5	2.0	1.71	0.18	0.87	0.0001	0.040
1985-1989	27	10.7	2.7	1.75	0.16	0.64	0.0003	0.034
China								
1985-1989	150	78.1	13.3	143	1.84	10.8	0.032	0.45
China (Taiwan Province)								
1985-1989		3.4		1.49	0.44			
Czechoslovakia [e]								
1975-1979	11	5.08	1.27	3.16	0.62	2.50	0.003	0.18
1980-1984	11	6.89	2.22	4.48	0.65	2.02	0.003	0.092
1985-1989	9.5	8.56	2.65	5.84	0.68	2.21	0.003	0.13
Denmark								
1975-1979	2.5	4.28		1.01	0.24		0	0
1980-1984	2.4	4.02		0.64	0.16		0.0002	0.016
1985-1989	2.6	3.82		0.43	0.11		0.0000	0.006
Finland [f g h]								
1975-1979	5.1	3.88	0.084	0.58	0.15	6.93	0.002	0.46
1980-1984	4.6	4.37	0.29	0.71	0.16	2.43	0.001	0.15
1985-1989	4.3	4.82	0.30	0.92	0.19	3.10	0.002	0.28
France [i]								
1975-1979		33.4		39.7	1.19		0.004	
1980-1984	45	49.0	6.05	28.3	0.58	4.67	0.005	
1985-1989	55	61.8	6.35	20.3	0.33	3.19	0.004	
German Dem. Rep.								
1980-1984	19	19.2	3.12	2.05	0.11	0.66		0.08
1985-1989	19	20.4	1.17	1.68	0.083	1.44		0.11
Hungary								
1975-1979		5.96	1.22	2.32	0.39	1.90	0.002	0.11
1980-1984		7.49	1.01	1.61	0.22	1.60	0.0009	0.088
1985-1989		7.26	0.98	1.49	0.21	1.53	0.0007	0.078
India								
1975-1979	41	6.50	3.64	3.75	0.58	1.03	0.004	0.21
1980-1984	61	8.00	3.97	2.76	0.35	0.70	0.001	0.15
1985-1989	82	10.4	5.42	3.54	0.34	0.65	0.001	0.14
Indonesia								
1975-1979		0.98	0.94	1.59	1.62	1.70	0.002	0.022
1980-1984		1.84	1.76	2.94	1.60	1.68	0.0006	0.009
1985-1989		2.30	2.19	3.84	1.67	1.75	0.001	0.015

Table 32 (continued)

Country and period [a]	Examinations (millions)	Monitored workers (thousands)	Measurably exposed workers (thousands)	Annual collective effective dose (man Sv)	Average annual effective dose: Per monitored worker (mSv)	Average annual effective dose: Per measurably exposed worker (mSv)	Distribution ratio: NR_{15} [b]	Distribution ratio: SR_{15}
Ireland								
1985-1989		1.46	0.12	0.55	0.38	4.69	0	0
Peru								
1980-1984		1.37		4.95	3.61			
1985-1989	0.30	1.48		5.10	3.45			
Spain								
1985-1989	23	34.3	30.9	25.9	0.76	0.84	0.004	0.12
Total of reported data [j]								
1975-1979		65.7		54.8	0.84		0.003	0.14
1980-1984		104		48.3	0.47		0.003	0.08
1985-1989		213		194	0.91		0.015	0.40
World [k]								
1975-1979		630		600	0.94		0.003	0.11
1980-1984		1060		720	0.68		0.003	0.05
1985-1989		1350		760	0.56		0.005 [l]	0.22 [l]
Dental practice								
Argentina								
1985-1989		0.070	0.044	0.033	0.46	0.74	0.014	0.42
Australia [c,d]								
1975-1979		1.16		0	0			
1985-1989		3.79	1.60	0.021	0.006	0.013	0	0
Canada								
1975-1979		13.1	0.97	0.42	0.032	0.44	0.0001	0.11
1980-1984		19.5	0.94	0.60	0.31	0.64	0.0001	0.13
1985-1989		24.4	0.94	0.64	0.026	0.68	0.0000	0.28
France [i]								
1975-1979		6.17		2.61	0.42		0.0003	
1980-1984		11.2	0.74	2.42	0.22	3.25	0.002	
1985-1989		16.7	0.86	1.97	0.12	2.31	0.001	
Germany, Fed. Rep. of								
1985-1989	17	7.82	0.18	0.39	0.05	2.16	0.0005	0.60
Hungary								
1975-1979		0.24	0.009	0.013	0.055	1.54	0	0
1980-1984		0.32	0.008	0.008	0.026	1.02	0	0
1985-1989		0.24	0.003	0.003	0.012	0.85	0	0
India								
1975-1979		0.37	0.21	0.17	0.45	0.80	0.0008	0.044
1980-1984		0.45	0.21	0.17	0.38	0.80	0.0008	0.060
1985-1989		0.63	0.32	0.24	0.38	0.74	0.003	0.19
Indonesia								
1975-1979		0.019	0.019	0.025	1.31	1.31	0	0
1980-1984		0.15	0.15	0.28	1.84	1.84	0	0
1985-1989		0.099	0.099	0.15	1.50	1.50	0.002	0.024
Ireland								
1985-1989		0.13	0.003	0.001	0.008	0.30		
Italy								
1985-1989		1.01	0.39	0.074	0.073	0.19	0.0005	0.28
Japan								
1975-1979	95	0.35	0.075	0.13	0.36	1.68		
1980-1984	99	1.75	0.20	0.34	0.20	1.69		
1985-1989	96	3.53	0.35	0.56	0.16	1.60		

Table 32 (continued)

Country and period [a]	Examinations (millions)	Monitored workers (thousands)	Measurably exposed workers (thousands)	Annual collective effective dose (man Sv)	Average annual effective dose		Distribution ratio	
					Per monitored worker (mSv)	Per measurably exposed worker (mSv)	NR_{15} [b]	SR_{15}
South Africa								
1975-1979		2.27	1.06	0.12	0.051	0.11	0	0
1980-1984		2.82	0.53	1.52	0.54	2.88	0.0007	0.64
1985-1989		3.33	0.37	4.49	1.35	12.2	0.002	0.18
Spain								
1985-1989	9.0	1.29	1.21	1.56	1.21	1.30	0.005	0.1
Switzerland [m]								
1975-1979		7.09		1.21	0.17		0.0009	0.066
1980-1984	2.1	9.13		0.96	0.11		0.0004	0.088
1985-1989		10.7		0.26	0.025		0.0000	0.015
United Kingdom [H1, W4]								
1980-1984	9.0	20		2	0.1			
1985-1989	9.0	20		2	0.1		0	0
United States [n]								
1975-1979		215		80	0.37			
1980-1984		259		60	0.23			
1985-1989	100	307	61	12	0.039	0.20		
Total of reported data [j]								
1975-1979		242		84.5	0.35		0.0004	0.077
1980-1984		322		68.8	0.21		0.0008	0.084
1985-1989		391		18.5	0.047		0.0003	0.12
World [k]								
1975-1979		370		120	0.32			
1980-1984		500		93	0.19			
1985-1989		480		25	0.05			
Nuclear medicine								
Argentina								
1985-1989		0.92	0.25	0.76	0.82	3.08	0.007	0.26
Australia [c d]								
1975-1979		0.67		0.20	0.30			
1985-1989		2.72	1.31	0.44	0.16	0.33	0	0
Brazil								
1985-1989		0.92	0.25	0.76	0.82	3.08	0.007	0.26
Canada								
1975-1979		0.57	0.41	1.08	1.90	2.63	0.012	0.13
1980-1984		0.85	0.55	1.53	1.81	2.80	0.005	0.046
1985-1989		1.14	0.83	2.24	1.96	2.71	0.004	0.039
China								
1985-1989	0.74	6.08	0.71	9.52	1.57	13.3	0.013	0.27
China (Taiwan Province)								
1985-1989		0.38		0.10	0.27			
Czechoslovakia [e]								
1975-1979		0.74	0.22	0.43	0.58	1.83	0.0012	0.035
1980-1984		1.08	0.67	0.99	0.92	1.48	0.0014	0.027
1985-1989		1.46	0.75	1.26	0.87	1.68	0.0006	0.011
Denmark								
1975-1979	0.067	0.45		0.34	0.76		0	0
1980-1984	0.073	0.48		0.30	0.62		0.0004	0.029
1985-1989	0.069	0.50		0.35	0.70		0	0

Table 32 (continued)

Country and period [a]	Examinations (millions)	Monitored workers (thousands)	Measurably exposed workers (thousands)	Annual collective effective dose (man Sv)	Average annual effective dose: Per monitored worker (mSv)	Average annual effective dose: Per measurably exposed worker (mSv)	Distribution ratio: NR_{15} [b]	Distribution ratio: SR_{15}
Finland [f g]								
1975-1979	0.060	0.60	0.018	0.074	0.12	4.11	0.0003	0.044
1980-1984	0.067	0.68	0.060	0.15	0.23	1.93	0.0009	0.072
1985-1989		0.75	0.11	0.17	0.23	1.62	0	0
France [h]								
1975-1979		2.76		3.25	1.18		0.002	
1980-1984		3.37	0.62	1.61	0.48	2.60	0.003	
1985-1989		3.21	0.54	1.03	0.32	1.92	0.003	
German Dem. Rep.								
1980-1984		0.81	0.20	0.54	0.67	2.68		0
1985-1989		0.83	0.15	0.43	0.51	2.84		0.016
Hungary								
1975-1979		0.36	0.029	0.048	0.14	1.66	0.0005	0.086
1980-1984		0.54	0.092	0.18	0.33	1.93	0.002	0.14
1985-1989		0.72	0.14	0.22	0.31	1.62	0.0004	0.014
India								
1975-1979		0.41	0.12	0.22	0.54	1.82	0.003	0.21
1980-1984		0.49	0.22	0.39	0.80	1.82	0.004	0.10
1985-1989	0.17	0.61	0.30	0.52	0.85	1.75	0.005	0.12
Indonesia								
1980-1984		0.009	0.009	0.011	1.23	1.23	0	0
1985-1989		0.013	0.013	0.015	1.20	1.20	0	0
Ireland								
1985-1989			0.023	0.012		0.5		0
Mexico [e]								
1985-1989		0.42	0.26	1.21	2.88	4.63	0.033	0.33
Peru								
1980-1984		0.12		0.43	3.73			
1985-1989		0.13		0.35	2.75			
Spain								
1985-1989		0.92	0.83	1.61	1.74	1.93	0.009	0.11
Total of reported data [i]								
1975-1979		5.66		5.21	0.92		0.003	0.11
1980-1984		7.91		5.72	0.72		0.003	0.048
1985-1989		15.9		16.6	1.04		0.006	0.17
World [k]								
1975-1979		61		62	1.01		0.002	0.087
1980-1984		81		85	1.04		0.002	0.033
1985-1989		90		85	0.95		0.004 [l]	0.096 [l]
Radiotherapy								
Argentina								
1985-1989	0.04	0.27	0.077	0.28	1.04	3.61	0.004	0.097
Australia [c d]								
1975-1979		0.64		1.47	2.30			
1985-1989	0.03	0.78	0.63	0.27	0.34	0.42	0.002	0.17
Brazil								
1985-1989		0.72	0.24	0.90	1.24	3.73	0.018	0.44
Canada								
1975-1979	0.46	0.54	0.35	0.75	1.40	2.14	0.006	0.27
1980-1984	0.49	0.62	0.36	0.63	1.01	1.78	0.003	0.078
1985-1989	0.52	0.72	0.43	0.59	0.82	1.38	0.0008	0.049

Table 32 (continued)

Country and period [a]	*Examinations* (millions)	*Monitored workers* (thousands)	*Measurably exposed workers* (thousands)	*Annual collective effective dose* (man Sv)	*Average annual effective dose*		*Distribution ratio*	
					Per monitored worker (mSv)	*Per measurably exposed worker* (mSv)	NR_{15} [b]	SR_{15}
China								
1985-1989	0.103	2.54	0.35	3.54	1.39	10.0	0.015	0.31
China (Taiwan Province)								
1985-1989		0.36		0.058	0.16			
Czechoslovakia [c]								
1975-1979	0.009	0.76	0.38	1.43	1.89	3.82	0.004	0.049
1980-1984	0.011	1.11	0.69	2.08	1.87	3.01	0.005	0.082
1985-1989	0.014	1.29	0.63	1.83	1.42	2.90	0.004	0.10
Denmark								
1975-1979		0.92		1.95	2.12		0.034	0.37
1980-1984		1.01		1.12	1.11		0.008	0.17
1985-1989	0.015	1.01		0.38	0.38		0.0004	0.022
Finland [f g]								
1980-1984		0.25	0.026	0.054	0.22	2.08	0.0008	0.30
1985-1989		0.24	0.018	0.026	0.095	1.44	0.0007	0.25
France [i]								
1975-1979		4.77		8.77	1.84		0.009	
1980-1984		6.01	1.30	6.08	1.01	4.68	0.008	
1985-1989		6.49	1.23	3.97	0.61	3.22	0.006	
German Dem. Rep.								
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
Hungary								
1975-1979		0.36	0.14	0.73	2.05	5.15	0.034	0.36
1980-1984		0.45	0.14	0.61	1.36	4.31	0.016	0.24
1985-1989		0.55	0.15	0.61	1.10	3.97	0.012	0.23
India								
1975-1979	0.052	2.49	1.43	3.91	1.57	2.73	0.017	0.39
1980-1984		2.98	1.53	3.39	1.14	2.22	0.009	0.30
1985-1989	0.13	4.17	2.28	3.94	0.95	1.73	0.007	0.23
Indonesia								
1975-1979		0.091	0.086	0.19	2.10	2.20	0	0
1980-1984		0.31	0.30	0.50	1.60	1.68	0.0007	0.017
1985-1989		0.23	0.22	0.35	1.55	1.63	0.003	0.039
Ireland								
1985-1989		0.30	0.14	0.15	0.50	1.05	0	0
Mexico [e]								
1985-1989		0.31	0.26	0.88	2.84	3.41	0.026	0.33
Peru								
1980-1984		0.088		0.54	6.18			
1985-1989	0.004	0.094		0.48	5.17			
Spain								
1985-1989		1.01	0.96	0.88	0.86	0.91	0.001	0.020
Total of reported data [j]								
1975-1979		9.31		16.5	1.78		0.012	0.30
1980-1984		13.3		15.3	1.15		0.008	0.19
1985-1989		18.8		16.6	0.88		0.007	0.21
World [k]								
1975-1979		84		190	2.23			
1980-1984		110		180	1.58			
1985-1989		110		100	0.87			

Table 32 (continued)

Country and period [a]	Examinations (millions)	Monitored workers (thousands)	Measurably exposed workers (thousands)	Annual collective effective dose (man Sv)	Average annual effective dose		Distribution ratio	
					Per monitored worker (mSv)	Per measurably exposed worker (mSv)	NR_{15} [b]	SR_{15}
Veterinary medicine								
Australia [c d]								
1975-1979		0.39		0.055	0.14		0	0
1985-1989		2.07	0.89	0.018	0.009	0.020	0	0
Canada								
1975-1979		0.77	0.24	0.17	0.22	0.73	0.0008	0.11
1980-1984		1.27	0.22	0.16	0.13	0.74	0.0002	0.026
1985-1989		1.52	0.31	0.17	0.11	0.56	0	0
Czechoslovakia [e]								
1975-1979		0.17		0.10	0.59			
1980-1984		0.23		0.14	0.62			
1985-1989		0.25		0.13	0.52			
Denmark								
1975-1979		0.49		0.022	0.045		0	0
1980-1984		0.52		0.030	0.059		0.0004	0.17
1985-1989		0.71		0.024	0.034		0	0
Finland [f g h]								
1980-1984			0.010	0.012		1.20		0
1985-1989			0.018	0.026		1.44		0
France [i]								
1985-1989		1.19	0.087	0.020	0.17	2.30	0.003	
Hungary								
1975-1979		0.061	0.009	0.045	0.55	5.07	0.010	0.42
1980-1984		0.11	0.007	0.006	0.058	0.94	0	0
1985-1989		0.14	0.010	0.028	0.20	2.78	0.003	0.24
India								
1975-1979		0.062	0.021	0.011	0.17	0.51	0	0
1980-1984		0.080	0.026	0.016	0.20	0.61	0	0
1985-1989		0.092	0.035	0.019	0.20	0.53	0.002	0.20
Ireland								
1985-1989		0.04	0.002	0.001	0.017	0.33	0	0
Japan [f] [H10]								
1985-1989		18.0		1.40	0.078			
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
Switzerland								
1975-1979		0.44		0.12	0.27		0.0006	0.032
1980-1984		0.59		0.13	0.22		0	0
1985-1989		1.03		0.050	0.049		0	0
United Kingdom [W4]								
1985-1989		4		0.4	0.1		0	0
United States [q] [E1]								
1975-1979		18.1	6.2	14	0.77	2.26		
1980-1984		21	12	13	0.62	1.08		
1985-1989		85	38	36	0.42	0.95		
Total of reported data [j]								
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		0.0001	0.016

Table 32 (continued)

Country and period [a]	Examinations (millions)	Monitored workers (thousands)	Measurably exposed workers (thousands)	Annual collective effective dose (man Sv)	Average annual effective dose		Distribution ratio	
					Per monitored worker (mSv)	Per measurably exposed worker (mSv)	NR_{15} [b]	SR_{15}
World [k]								
1975-1979		48		25	0.52			
1980-1984		65		26	0.40			
1985-1989		160		52	0.32			
All (human) medical uses of radiation (excluding veterinary medicine)								
Argentina								
1985-1989		3.45	1.20	3.74	1.08	3.12	0.13	0.48
Australia [c d]								
1975-1979		6.23		3.45	0.55			
1985-1989		15.8	8.96	1.11	0.07	0.12	0.0001	0.041
Brazil [D2]								
1985-1989		76	23	115	1.51	4.96		
Canada								
1975-1979		39.6	11.8	10.4	0.26	0.88	0.0005	0.080
1980-1984		51.7	7.88	8.30	0.16	1.05	0.0002	0.044
1985-1989		62.9	10.8	9.18	0.15	0.85	0.0002	0.058
China								
1985-1989		86.8	14.4	156	1.80	10.9	0.030	0.43
China (Taiwan Province)								
1980-1984		3.08		1.77	0.57			
1985-1989		3.98		1.96	0.49			
Czechoslovakia [e]								
1975-1979		6.78	1.89	5.16	0.76	2.73	0.003	0.13
1980-1984		9.38	3.62	7.80	0.83	2.15	0.003	0.079
1985-1989		11.6	4.04	9.12	0.78	2.25	0.003	0.10
Denmark								
1975-1979		6.13		3.32	0.54		0.005	0.22
1980-1984		6.02		2.08	0.35		0.002	0.10
1985-1989		6.04		1.18	0.20		0	0.011
Finland [f]								
1975-1979		4.98	0.18	1.17	0.23	6.55	0.004	0.45
1980-1984		5.60	0.58	1.23	0.21	2.10	0.001	0.12
1985-1989		6.18	0.49	1.22	0.20	2.50	0.001	0.21
France [i]								
1975-1979		40.9		49.3	1.21		0.004	
1980-1984		59.2	8.06	36.0	0.61	4.46	0.006	
1985-1989		73.7	8.19	25.1	0.34	3.06	0.003	
German Dem. Rep.								
1980-1984		24.6		3.34	0.14			
1985-1989		24.9	1.29	2.56	0.10	1.99	0.001	0.18
Germany, Fed. Rep. of								
1980-1984		134	22.2	26.2	0.20	1.18	0.0008	0.14
1985-1989		185	21.9	23.5	0.13	1.07	0.0005	0.16
Hungary								
1975-1979		7.80	1.43	3.19	0.41	2.23	0.003	0.16
1980-1984		9.15	1.26	2.41	0.26	1.91	0.002	0.13
1985-1989		9.07	1.29	2.34	0.26	1.82	0.001	0.11
India								
1975-1979		9.58	5.22	7.89	0.82	1.51	0.007	0.30
1980-1984		11.6	5.74	6.56	0.57	1.14	0.003	0.22
1985-1989		15.2	8.03	8.02	0.53	1.00	0.003	0.17

Table 32 (continued)

Country and period [a]	Examinations (millions)	Monitored workers (thousands)	Measurably exposed workers (thousands)	Annual collective effective dose (man Sv)	Average annual effective dose		Distribution ratio	
					Per monitored worker (mSv)	Per measurably exposed worker (mSv)	NR_{15} [b]	SR_{15}
Indonesia								
1975-1979		1.07	1.02	1.78	1.67	1.75	0.002	0.02
1980-1984		2.16	2.06	3.44	1.60	1.68	0.003	0.01
1985-1989		2.53	2.41	4.24	1.68	1.77	0.003	0.01
Ireland								
1985-1989		1.69	0.28	0.22	0.13	0.78	0	0
Italy								
1985-1989		44.6	12.6	21.0	0.47	1.66	0.004	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	38.6	46.6	0.33	1.21		
Mexico [c]								
1985-1989		0.73	0.52	2.09	2.86	4.02	0.030	0.24
Peru								
1980-1984		1.58		7.03	4.46			
1985-1989		1.70		7.14	4.20			
Portugal [C1]								
1985-1989		3.83	0.97	2.01	0.52	2.06	0.003	
South Africa								
1975-1979		8.76	5.49	0.57	0.065	0.103	0.000	0.085
1980-1984		10.7	4.13	7.37	0.687	1.79	0.006	0.52
1985-1989		12.1	2.64	9.53	0.787	3.61	0.005	0.23
Spain								
1985-1989		37.7	34.0	29.3	0.78	0.86	0.004	0.12
Sweden [f]								
1975-1979		11.5	1.29	2.84	0.25	2.21	0.006	
1980-1984		12.8	1.38	2.53	0.20	1.83	0.004	
1985-1989		13.2	3.66	3.13	0.24	0.86	0.002	
Switzerland								
1975-1979		21.5		6.20	0.29		0.001	0.12
1980-1984		30.1		4.97	0.17		0.001	0.092
1985-1989		36.1		1.83	0.05		0.000	0.026
United Kingdom [H1, W4]								
1980-1984		39		28	0.71			
1985-1989		40		8.4	0.21			
United States [g]								
1975-1979		485		460	0.95			
1980-1984		584		410	0.70			
1985-1989		734	267	280	0.38	1.05		
Total of reported data								
1975-1979		671		577	0.86		0.003	0.16
1980-1984		1060		588	0.55		0.002	0.11
1985-1989		1520		644	0.42		0.007 [i]	0.34 [i]
World								
1975-1979		1280	650	993	0.78	1.5	0.003	0.14
1980-1984		1890	520	1140	0.60	1.7	0.002	0.10
1985-1989		2220	590	1030	0.47	1.7	0.009 [i]	0.24 [i]

[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 some of the years in the periods of interest here.

[b] The values of NR_{15} are for the monitored workforce. Values for the exposed workforce can also be estimated where data are given for both monitored and measurably exposed workers.

Table 32 (*continued*)

[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] The number of workers and the collective dose have been scaled up by a factor of 1.5, since the reported data included only workers in that part of the country that was to become the Czech Republic, which contained two thirds of the country's population.

[f] The numbers of examinations include those in dental practice, which amount to about 1 million per year.

[g] Some 14% of the total collective dose from all medical uses of radiation has yet to be assigned to one or other of the various categories. Consequently, the reported doses may be small underestimates, particularly in 1975-1985, where most of the doses yet to be assigned exist.

[h] Reported doses are overestimates because the dosimeter is calibrated in terms of skin surface dose and is worn above aprons when they are used. For diagnostic x-ray radiology preliminary studies indicate that the overestimate may be a factor in the range of 3-30.

[i] 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.

[j] 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.

[k] The estimates are extrapolations of regional values based on the gross national product (GNP); because of insufficient data, the estimates of NR_{15} and SR_{15} are averages of the 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.

[l] The apparent increase in the ratios in the third period is consequent upon data for China (for which the values of these ratios are much larger than the average) only being included in the period 1985-1989. Excluding China, there is a downward trend in the values over the whole period.

[m] Data for dentists in private practice only.

[n] Data from [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.

[o] In the absence of data for 1985-1989, the data for 1990 have been assumed representative.

[p] Data are 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 the remainder on small animals.

[q] The values for 1985 (the period 1985-1989) are based on extrapolations of earlier data.

[r] 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 3-30; about 60% of the occupational exposures reported for all medical uses of radiation are currently reported to arise in diagnostic radiology.

Table 33
Worldwide exposure from all medical uses of radiation [a]

Country/region	*Monitored workers* [b] *(thousands)*	*Average annual collective effective dose* [c] *(man Sv)*	*Average annual individual dose to monitored workers (mSv)*	*Collective effective dose per unit GNP* [d] *(man Sv per 10^{12} SUS)*	*Collective effective dose per unit population (man Sv per 10^{9})*
1975-1979					
East and south-east Asia [e]	4 (0.3%)	7 (0.7%)	1.7	44	21
Eastern Europe [f]	190 (15%)	110 (11%)	0.57	94	280
Indian subcontinent	12 (0.9%)	10 (1%)	0.82	81	12
Latin America					
OECD except United States	360 (28%)	220 (22%)	0.61	74	490
United States	490 (38%)	460 (46%)	0.95	250	2100
Remainder [g]	230 (18%)	190 (19%)	0.84	160	97
Total	1300	990	0.78	130	230
1980-1984					
East and south-east Asia [e]	10 (0.5%)	16 (1%)	1.6	37	41
Eastern Europe [f]	460 (24%)	150 (13%)	0.31	64	350
Indian subcontinent	15 (0.8%)	9 (0.7%)	0.57	33	9
Latin America	60 (3%)	270 (25%)	4.5	350	650
OECD except United States	610 (32%)	210 (18%)	0.35	43	450
United States	580 (31%)	410 (36%)	0.70	120	1700
Remainder [g]	160 (8%)	90 (8%)	0.55	79	48
Total	1900	1100	0.60	87	240
1985-1989					
Asia [h]	96 (4%)	170 (17%)	1.8	440	140
East and south-east Asia [e]	17 (0.8%)	29 (3%)	1.7	56	66
Eastern Europe [f]	430 (19%)	130 (13%)	0.31	38	300
Indian subcontinent	19 (0.9%)	10 (1%)	0.53	30	9
Latin America	110 (5%)	180 (17%)	1.6	220	400
OECD except United States	740 (33%)	190 (19%)	0.27	24	370
United States	730 (33%)	280 (27%)	0.38	58	1100
Remainder [g]	75 (3%)	35 (3%)	0.47	56	42
Total	2200	1000	0.47	54	190

[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 contribution of that practice to the total number of monitored workers in medicine.
[c] The numbers in parentheses are the percentage contribution of that practice to the collective dose from all medical uses of radiation.
[d] The normalized collective doses per unit GNP for the three five-year periods are expressed, respectively, in terms of 1977, 1983 and 1989 prices; direct comparison between the values for different periods is possible only after correcting for these different price bases.
[e] Non-centrally-planned economies in east and south-east Asia.
[f] Including the whole of the former USSR.
[g] 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.
[h] Centrally-planned economies in east and south-east Asia.

Table 34
Summary of worldwide exposures from medical uses of radiation [a]

Practice	*Monitored workers* [b] *(thousands)*	*Annual average collective effective dose* [c] *(man Sv)*	*Annual average individual dose to monitored workers (mSv a^{-1})*	NR_{15} [d]	SR_{15} [d]
1975-1979					
Diagnostic radiology	630 (55%)	600 (62%)	0.94	0.003	0.11
Dental practice	370 (32%)	120 (12%)	0.32	0.0004	0.077
Nuclear medicine	61 (5%)	62 (6%)	1.01	0.002	0.087
Radiotherapy	84 (7%)	190 (20%)	2.23	0.012	0.30
All medicine	1300	990	0.78	0.003	0.14
1980-1984					
Diagnostic radiology	1100 (61%)	720 (67%)	0.68	0.003	0.05
Dental practice	500 (28%)	93 (9%)	0.19	0.0008	0.084
Nuclear medicine	81 (5%)	85 (8%)	1.04	0.002	0.033
Radiotherapy	110 (6%)	180 (17%)	1.58	0.008	0.19
All medicine	1900	1100	0.60	0.002	0.10
1985-1989					
Diagnostic radiology	1400 (67%)	760 (78%)	0.56	0.005	0.22
Dental practice	480 (23%)	25 (3%)	0.05	0.0003	0.12
Nuclear medicine	90 (4%)	85 (9%)	0.95	0.004	0.096
Radiotherapy	110 (5%)	100 (10%)	0.87	0.007	0.21
All medicine	2200	1000	0.47	0.009	0.24

[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 contribution of that practice to the total number of monitored workers in medicine.
[c] The numbers in parentheses are the percentage contribution of that practice to the collective dose from all medical uses of radiation.
[d] The values of NR_{15} and SR_{15} should only be regarded as indicative of worldwide experience. Reported data on these ratios were far fewer than for other quantities of interest (e.g. collective dose, monitored workers etc.) and were insufficient to form the basis for more reliable and representative estimate of worldwide levels.

Table 35
Employment in underground mining worldwide
[C20]

Country	*Number of miners (thousands)*		
	Coal mining	*Other mining*	*Total*
China	1594	64	1658
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	3908 (84%)	756 (16%)	4664 (100%)

Table 36
Exposures to radon and decay products in non-uranium mines

Country	*Year*	*Coal mining*			*Other mining*			*Ref.*
		Number of mines	*Exposure (WLM a^{-1})*	*% above 2 WLM a^{-1}*	*Number of mines*	*Exposure (WLM a^{-1})*	*% above 2 WLM a^{-1}*	
Australia	1991	3	0.2	0	23	0.1	0	[H5]
Canada	1980s				4	0.4	2	[A1]
France	1981	3	0.2	0	5	1.0	8	[B14]
Germany	1990	20	0.1	0				[R5]
	1991				45	1.4	18	[S10]
India	1980s	5	0.02	0				[M12]
	1980s				22	0.8	9	[N6]
Italy	1970s				35	1.2	8	[S11]
Poland	1980s	71	0.3	0.2	26	0.1	0	[D3]
South Africa	1970s				25	1.7	10	[G3]
	1990				40	0.31		[S7]
USSR		47	0.04		26	0.85		[P1]
United Kingdom	1980s	220	0.1	0				[D5]
	1990				41	0.45	7	[B15]
United States	1975	223	0.1	<1	10	0.5	4	[R6]
	1990				99 [a]	1.2		[B12]
	1985				86 [b]	0.12		[E3]
Yugoslavia	1970s	5	0.2	0				[K6]
	1980s				2	1.7	50	[K6]

[a] Metal mines.
[b] Non-metal mines.

Table 37
Doses to non-uranium miners in the former USSR and in the United States from inhalation of radon and its decay products

Type of mine	*Measurement period*	*Number of mines*	*Number of workers (thousands)*	*Average annual effective dose (mSv)* [a] [b]
Former USSR [P1]				
Coal				0.2 (0.1-0.9)
Other				4.8 (0.02-24)
United States (metal mines) [c]				
Iron	1985		1	6.7
Copper	1985		2.2	0.7
Lead/zinc	1985		3.9	13
Gold	1985		0.58	6.7
Silver	1985		2.9	1.3
Molybdenum	1985		2.2	1.3
Tungsten	1985		0.06	13
Platinum	1985		1	6.7
Total		99	13.8	6.7
United States (non-metal mines) [c]				
Oil shale	1985		0.25	0.07
Limestone	1985		0.85	0.2
Marble	1985		0.08	2
Clay	1985		0.04	4.7
Fluorspar	1985		0.05	0.33
Potash, soda, borate	1985		2.3	0.13
Phosphate	1985		0.1	20
Salt	1985		1.5	0.7
Gypsum	1985		0.08	1.3
Talc	1985		0.2	4.7
Non-metallic minerals	1985		0.04	0.2
Gilsonite	1985		0.11	0.13
Lime	1985		0.01	5.4
Total		86	5.5	0.67

[a] Range of values in parentheses.
[b] The doses reported in [E3, P1] were derived using a conversion factor of 10 mSv WLM^{-1} for exposure to radon progeny. The doses tabulated have been modified from those reported using a conversion factor of 5.6 mSv WLM^{-1}.
[c] Data from [E3]; they are based on measurements at about 40% of mines in the United States.

Table 38
Worldwide collective dose from inhalation of radon and its decay products from underground mining (excluding uranium) and its distribution between countries

Country	*Number of miners* [a] *(thousands)*	*Exposure to radon progeny* [b]	
		Annual collective effective dose (man Sv)	*Average annual effective dose (mSv)*
Coal mines			
Germany	105	59	0.56
India	669	74	0.11
Poland	251	430	1.7
USSR	840	170	0.2
United Kingdom	46	26	0.56
United States	51	29	0.56
Other	1940	740	0.38
Total	3910	1530	0.38
Other mines (excluding uranium) [c]			
Germany	4	31	7.8
India	10	45	4.5
Poland	10	5.6	0.56
South Africa [d]	340	1900	5.6
USSR	40	190	4.8
United Kingdom	2	5	2.5
United States [e]	48 [f]	240	4.9
Other	334	1800	5.4
Total [g]	700	3780	5.4
All underground mines (excluding uranium mines)			
Total	4610	5310	1.2

[a] Unless otherwise indicated, number of miners is taken from Table 35. 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 36 assuming a conversion factor of 5.6 mSv WLM^{-1}.
[c] The numbers of miners include those working in uranium mines and the estimated collective doses are, therefore, overestimates; this is corrected for 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 [S7] which are representative for 1990; somewhat higher levels were reported in the 1970s [G3] (see Table 36).
[e] Exposure data taken from [E3] (see Table 36).
[f] Value taken from [E3]; it is for all underground miners in the United States except those working in coal and uranium mines.
[g] Uranium miners have been excluded from the total.

Table 39
Summary of occupational exposures to natural radiation (excluding uranium mining) [a]

Occupation or practice	*Number of workers (thousands)*	*Worldwide annual collective effective dose (man Sv)*	*Average annual effective dose (mSv)*
Coal mining	3900	3400	0.9
Other mining [b]	700	4100	6
Aircrew	250	800	3
Other [c]	300	<300	<1
Total	5200	8600	1.7

[a] Estimated doses are appropriate for the latter half of the 1980s. In mining, somewhat higher individual and collective doses are likely to have been experienced previously. Collective doses to aircrew are likely to have been lower previously because air traffic growth over the period.
[b] Excluding uranium mining.
[c] Includes coal-fired power plants (~300,000 workers, collective dose: <60 man Sv) and extraction of mineral sands, phosphate ores and their subsequent use (collective dose: <200 man Sv).

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 3800 Bq (surgical removal of a contaminant); mean beta dose of 364 Gy in period 1977-1985 and annual gamma dose of 0.04 Gy 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 Dem 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 others 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 tip) and of 0.1 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 radiography source		1	Whole-body dose of 2-3 Gy
China [c]	1980	^{60}Co radiography source		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; moderate 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
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
El Salvador [a]	1989	^{60}Co irradiation facility		3	Whole-body doses 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
German Dem. 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)

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*
German Dem. Rep. Bohlen	1980	Analytical x-ray unit	Carelessness	1	Dose of 15-30 Sv to left hand; acute and chronic radio-dermatitis (2nd and 3rd degree)
German Dem. 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 radio-dermatitis (1st degree)
Germany, Fed. Rep.	1975	X-ray fluorescence equipment	Carelessness and technical faults during repair	1	Estimate dose of 30 Gy to the fingers; reddening of two fingers after 10 days
Germany, Fed. Rep.	1975	Welding seam test of x-ray equipment	Carelessness and technical defects	1	Estimated dose of ~2 Gy to the stomach region
Germany, Fed. 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, Fed. Rep.	1980	Radiogram unit	Defective equipment	2	Estimated dose of 23 Gy to the hand and an effective dose of 0.2 Sv
Germany, Fed. 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, Fed. 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 Győr	1977	Industrial defectoscope	Failure of equipment to withdraw source 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
Iraq [a]	1975	^{192}Ir radiography source		1	Whole-body dose of 0.3 Gy plus localized exposure of hand
Italy [a] Brescia	1975	^{60}Co industrial radiography source		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

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*
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
Norway [c] Kjeller	1982	^{60}Co industrial irradiation facility		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, all with an uncertainty of about 0.3 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
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
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
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

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] 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
United States [c] Oklahoma	1981	^{192}Ir radiography source		1	Whole-body and localized exposures
Tertiary education and accelerators					
German Dem. 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 Dem. 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 Dem. Rep. Berlin	1981	Analytical x-ray unit	Carelessness	1	Dose of 5 Gy to the left hand; acute radiodermatitis (1st degree)
German Dem. Rep. Berlin	1982	Analytical x-ray unit	Carelessness	1	Dose of 6 to 18 Gy to right forefinger; acute radiodermatitis (2nd degree)
German Dem. Rep. Leipzig	1983	Radiochemical laboratory	Explosion of vial containing a ^{241}Am solution	1	Committed effective dose of 0.076 Gy
German Dem. Rep. Jena	1988	Analytical x-ray unit	Carelessness	1	Dose of 3 Gy to left hand; acute radiodermatitis (1st degree)
German Dem. Rep. Trusetal	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, Fed. 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

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*
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
Medical uses of radiation					
Argentina Tucuman	1975	^{60}Co teletherapy	Failure of source's mechanical dispositive	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 to 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, Fed. Rep. of	1975	X-ray equipment	Probably carelessness in maintenance	1	Dose in excess of 1 Gy to head and upper torso
Germany, Fed. Rep. of	1977	^{192}Ir radiogram unit	Defective equipment	1	Estimated dose to hands 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 [I11].
[b] Data comprise a summary of cases of accidental exposure for which chromosome aberration analysis have been undertaken [L1].
[c] Data from [R3].
[d] Unclear whether exposed were workers or patients.

Table 41
Worldwide occupational exposures 1985-1989

Occupational category	*Average annual number of monitored workers (thousands)*	*Annual average collective effective dose (man Sv)*	*Annual average effective dose to monitored workers (mSv)*	*Normalized collective effective dose [man Sv (GW a)$^{-1}$]*	NR_{15}	SR_{15}
Nuclear fuel cycle						
Mining	260	1100	4.4	4.3	0.25 [a]	0.52 [a]
Milling	18	120	6.3	0.44	0.18 [a]	0.43 [a]
Enrichment	5	0.4	0.08	0.02	0	0
Fuel fabrication						
LWRs	24	11	0.45	0.07	0.0003	0.015
HWRs	1.1	1.9	1.7	0.22	0.003	0.042
Magnox	1.1	3.5	3.1	1.4	0.018	
AGRs	1.9	5.5	3.0	0.45	0.014	
Total	28	22	0.78	0.12	0.002	0.019
Reactor operation						
PWRs	230	500	2.2	4.3	0.034	0.328
BWRs	140	310	2.4	7.9	0.026	0.36
HWRs	18	67	3.4	6.2	0.066	0.48
LWGRs	13	170	13	17		
GCRs	31	24	0.75	3.2	0.0002	0.008
Other	3	1	0.4	1.4		
Total	430	1100	2.5	5.9	0.033	0.34
Fuel reprocessing						
Oxide	4	5.7	1.4	0.65	0.008	0.12
Magnox	8	31	3.8	11	0.092	
Total	12	36	3.0	3.2	0.064	0.12
Research	130	100	0.8	1.0	0.011	0.30
Total	880	2500	2.9	12 [b]	0.10 [a]	0.42 [a]
Defence activities						
Weapons	60	43	0.7			
Ships	190	170	0.9			
Other	130	37	0.3			
Total	380	250	0.7			
Industrial uses of radiation						
Total	560	510	0.9		0.009	0.31
Medical uses of radiation						
Total	2200	1000	0.5		0.009	0.24
Natural sources of radiation (excluding uranium mining)						
Coal mining	3900	3400	0.9			
Other mining	700	4100	6			
Air crew	250	800	3			
Other	~300	<300	<1			
Total	5200	8600	1.7			
Total of exposures						
Man-made	4000	4300	1.1		0.03 [a]	0.36 [a]
Natural sources	5200	8600	1.7			
Total	9200	13000	1.4			

[a] Values for mining and milling are averages of reported values and are overestimates for the revised conversion factor of 5.6 mSv WLM^{-1}. The entries for the totals are thus also overestimates. Excluding mining and milling from the averaging, the entries for total of the nuclear fuel cycle would be 0.03 and 0.32 and for total of man-made exposures 0.01 and 0.29 for NR_{15} and SR_{15}, respectively.

[b] Excluding fuel reprocessing.

Table 42
Trends in worldwide occupational exposures from man-made sources of radiation

Source	*Average annual collective effective dose (man Sv)*			*Average annual effective dose to monitored workers (mSv)*		
	1975-1979	*1980-1984*	*1985-1989*	*1975-1979*	*1980-1984*	*1985-1989*
Nuclear fuel cycle	2300	3000	2500	4.1	3.7	2.9
Defence activities	420	250	250	1.3	0.71	0.66
Industrial uses of radiation	870	940	510	1.6	1.4	0.9
Medical uses of radiation	1000	1140	1030	0.78	0.60	0.47
Total	5490	5330	4290	1.9	1.4	1.1
	Average annual number of monitored workers (thousands)			*Normalized collective effective dose [man Sv (GW a)$^{-1}$]*		
	1975-1979	*1980-1984*	*1985-1989*	*1975-1979*	*1980-1984*	*1985-1989*
Nuclear fuel cycle	560	800	880	18 [a]	17 [a]	12 [a]
Defence activities	310	350	380			
Industrial uses of radiation	530	690	560			
Medical uses of radiation	1280	1890	2220			
Total	2680	3730	4040			
	NR_{15}			*SR_{15}*		
	1975-1979	*1980-1984*	*1985-1989*	*1975-1979*	*1980-1984*	*1985-1989*
Nuclear fuel cycle [b]	0.20	0.16	0.10	0.63	0.55	0.42
Defence activities						
Industrial uses of radiation	0.010	0.007	0.009	0.35	0.28	0.31
Medical uses of radiation	0.003	0.002	0.009	0.14	0.10	0.24
Total	0.051	0.040	0.030	0.045	0.40	0.36

[a] Values excluding fuel reprocessing; the normalized doses would be greater by about 1 man Sv (GW a)$^{-1}$ for reprocessing of oxide fuel and about 10-15 man Sv (GW a)$^{-1}$ for reprocessing metal Magnox fuel (with the higher value pertaining to earlier times).

[b] Values are averages including mining and milling as reported and are thus overestimates for the revised conversion factor of 5.6 mSv WLM^{-1}. If mining and milling are excluded from the averaging, the values of NR_{15} would be about a factor of 3 lower and the values of SR_{15} would decreease by an absolute amount of about 0.1.

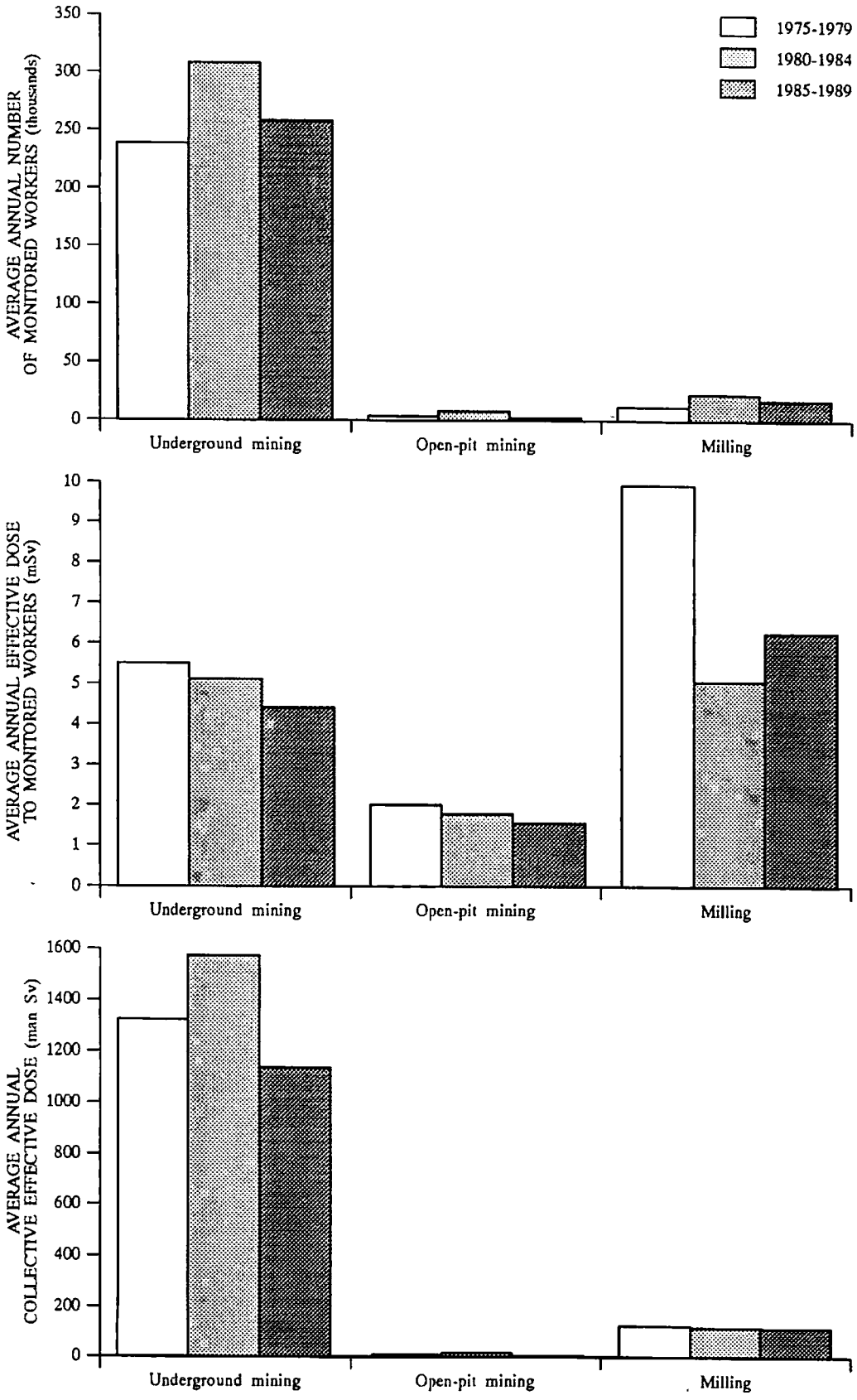


Figure I.
Number of workers and doses to workers in uranium mining and milling.

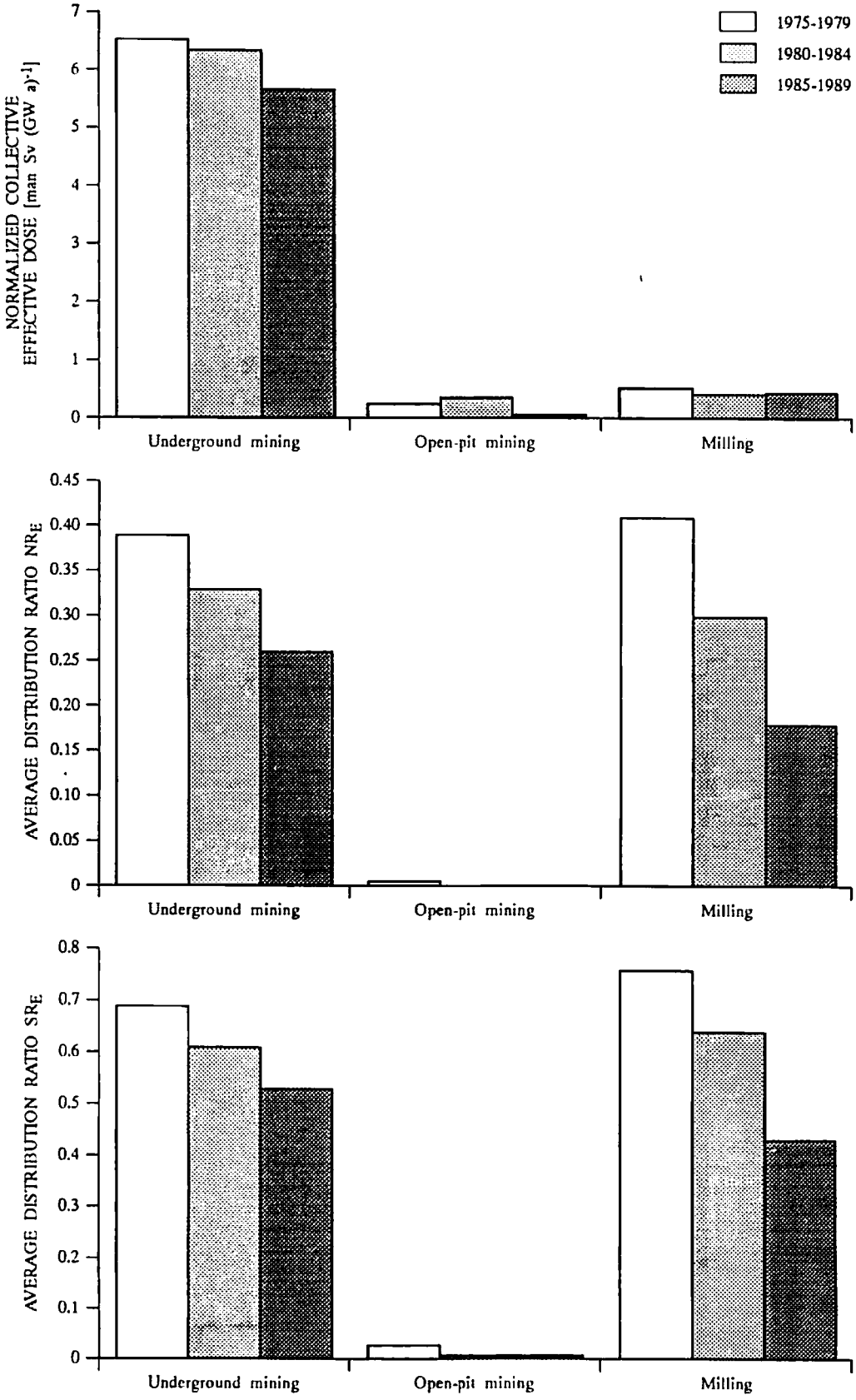


Figure II.
Normalized collective dose and distribution ratios for workers in uranium mining and milling.

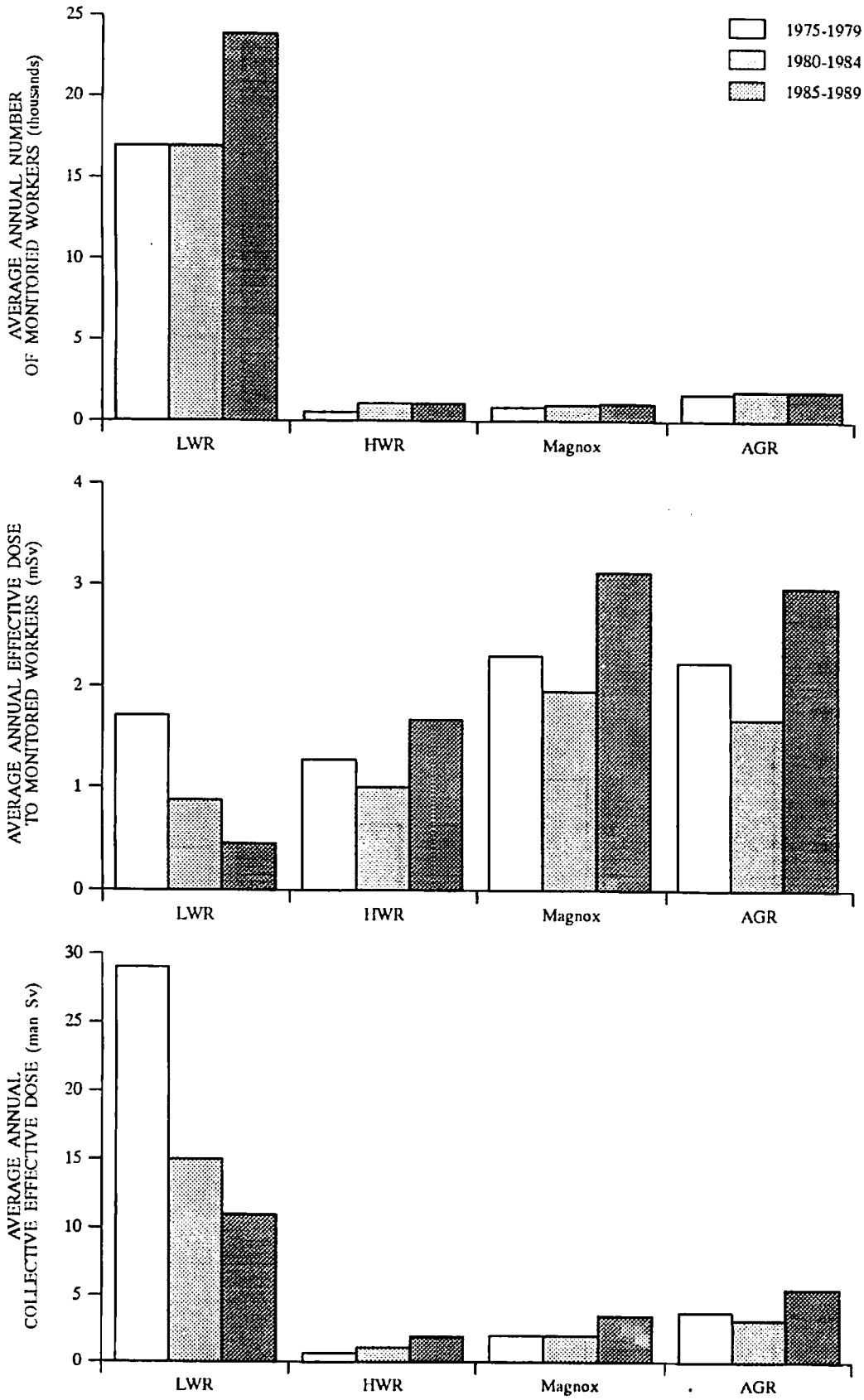


Figure III.
Number of workers and doses to workers in fuel fabrication.

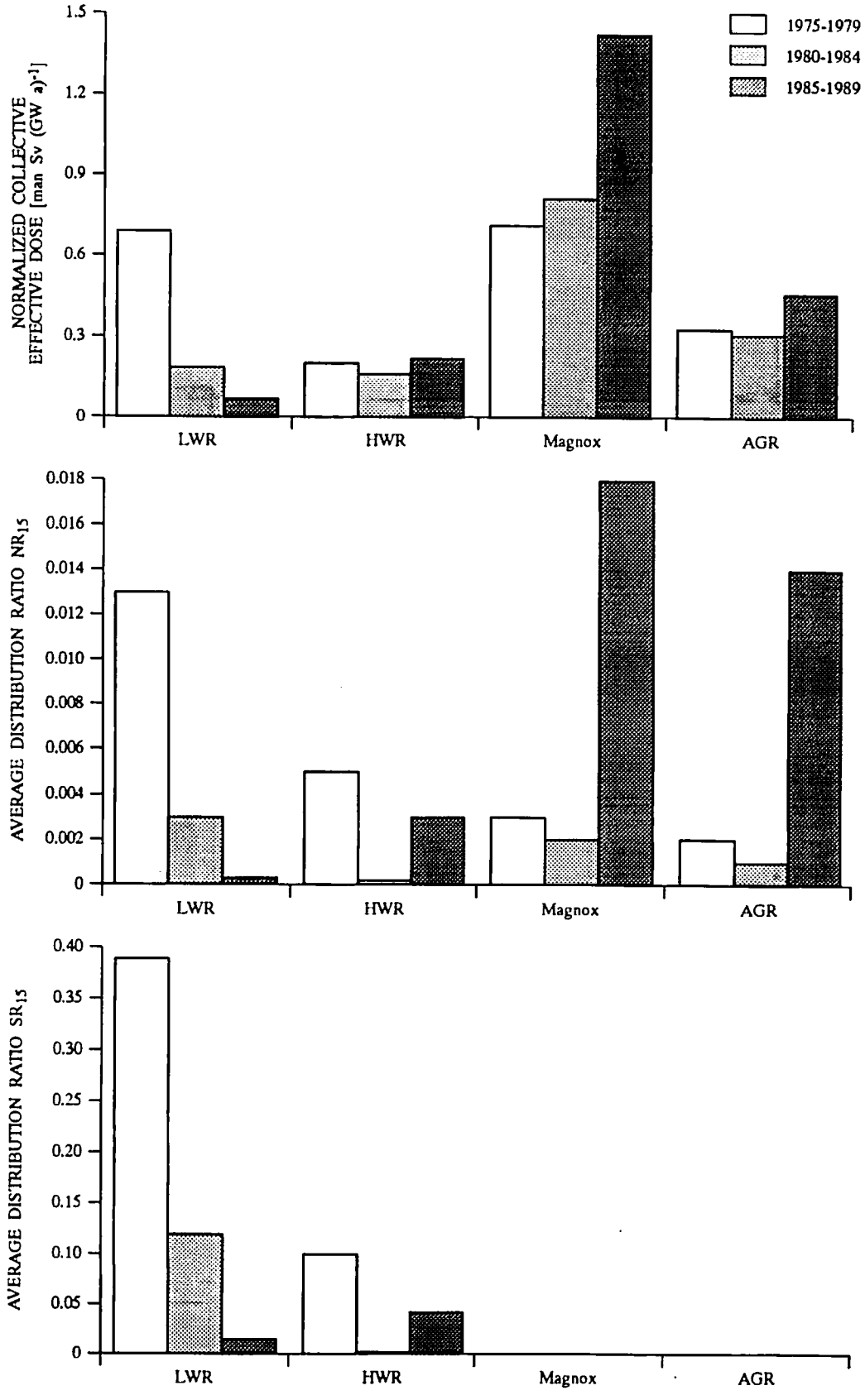


Figure IV.
Normalized collective dose and distribution ratios for workers in fuel fabrication.

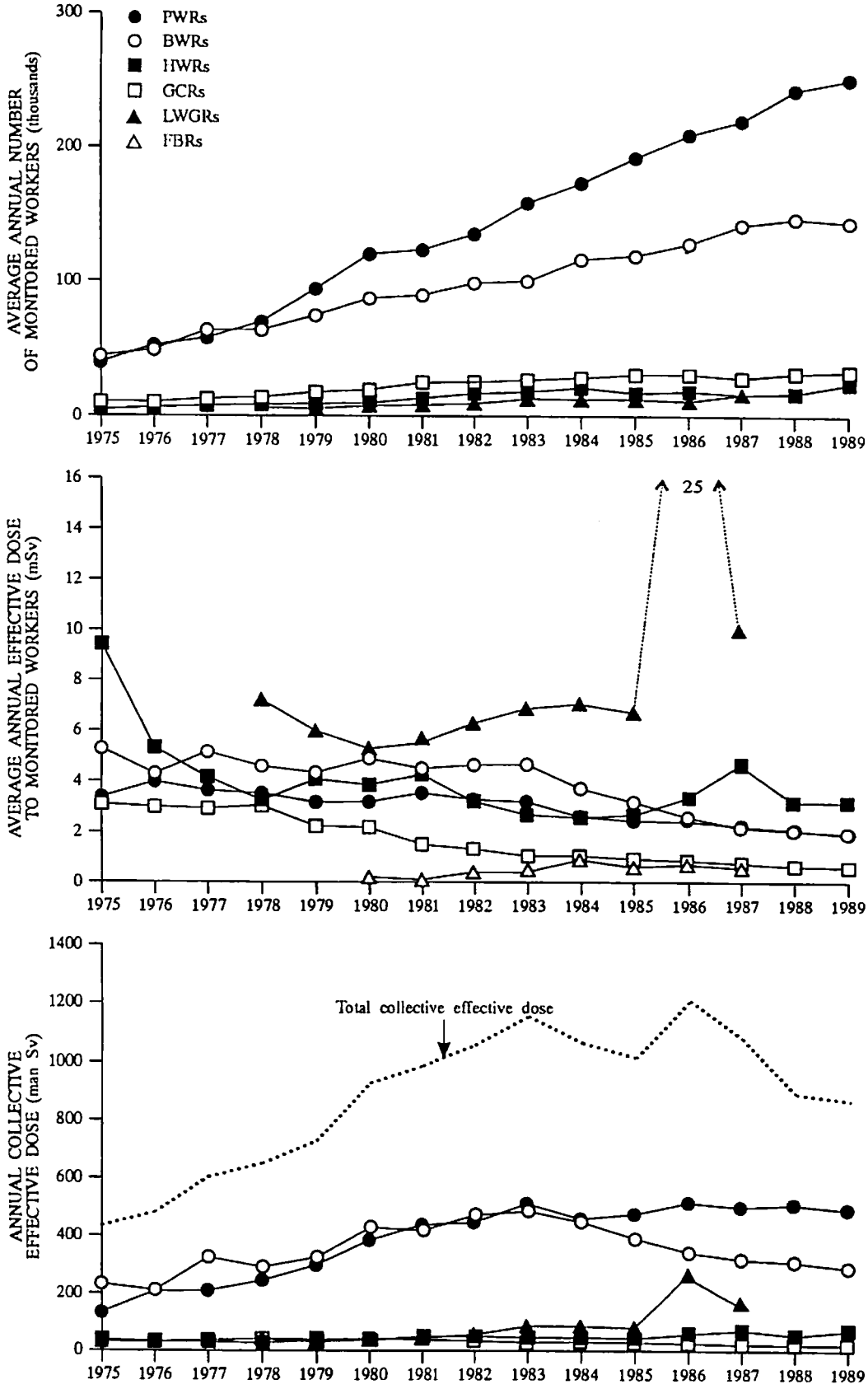


Figure V.
Number of workers and doses to workers in reactors.

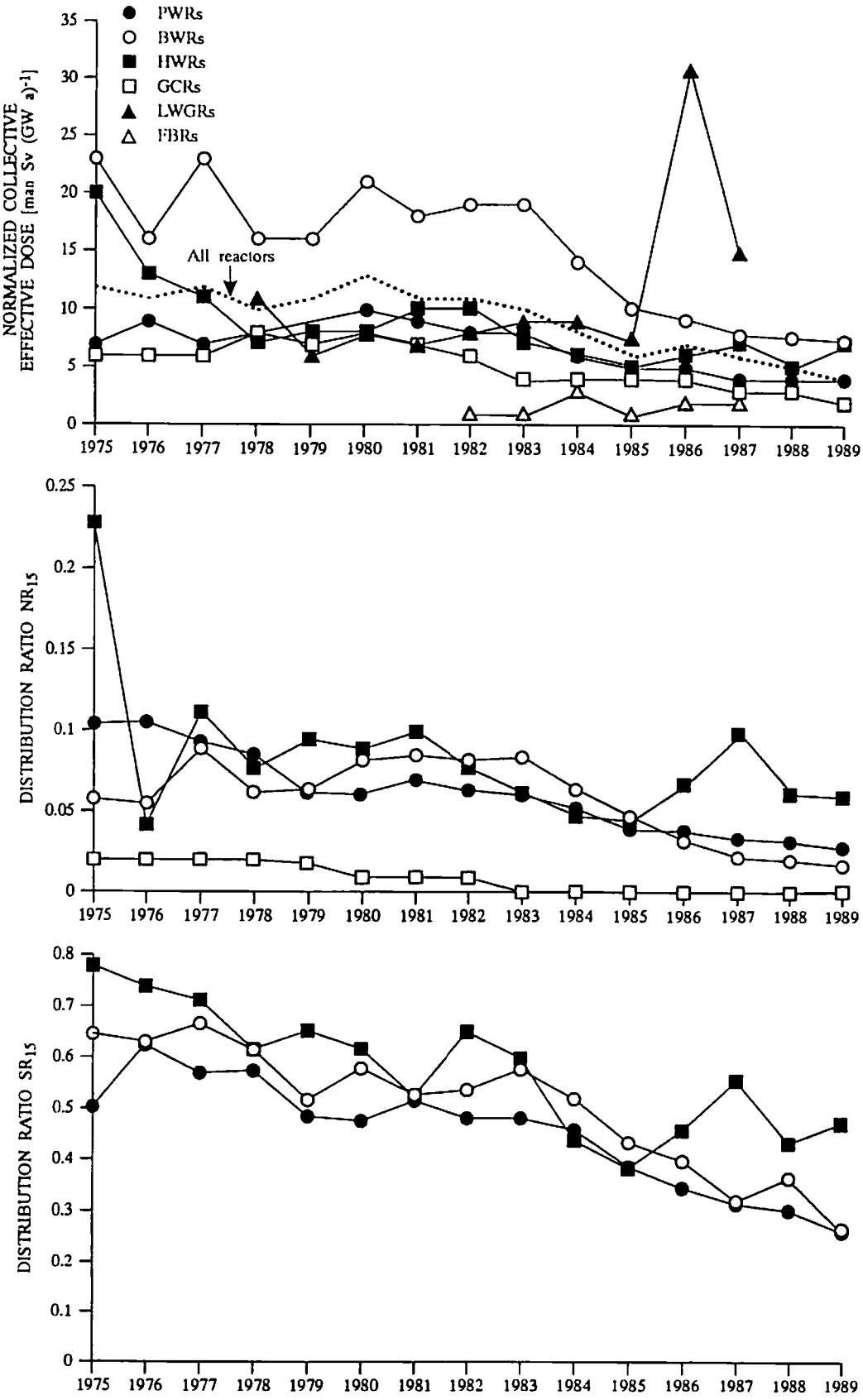


Figure VI.
Normalized collective dose and distribution ratios for reactor workers.

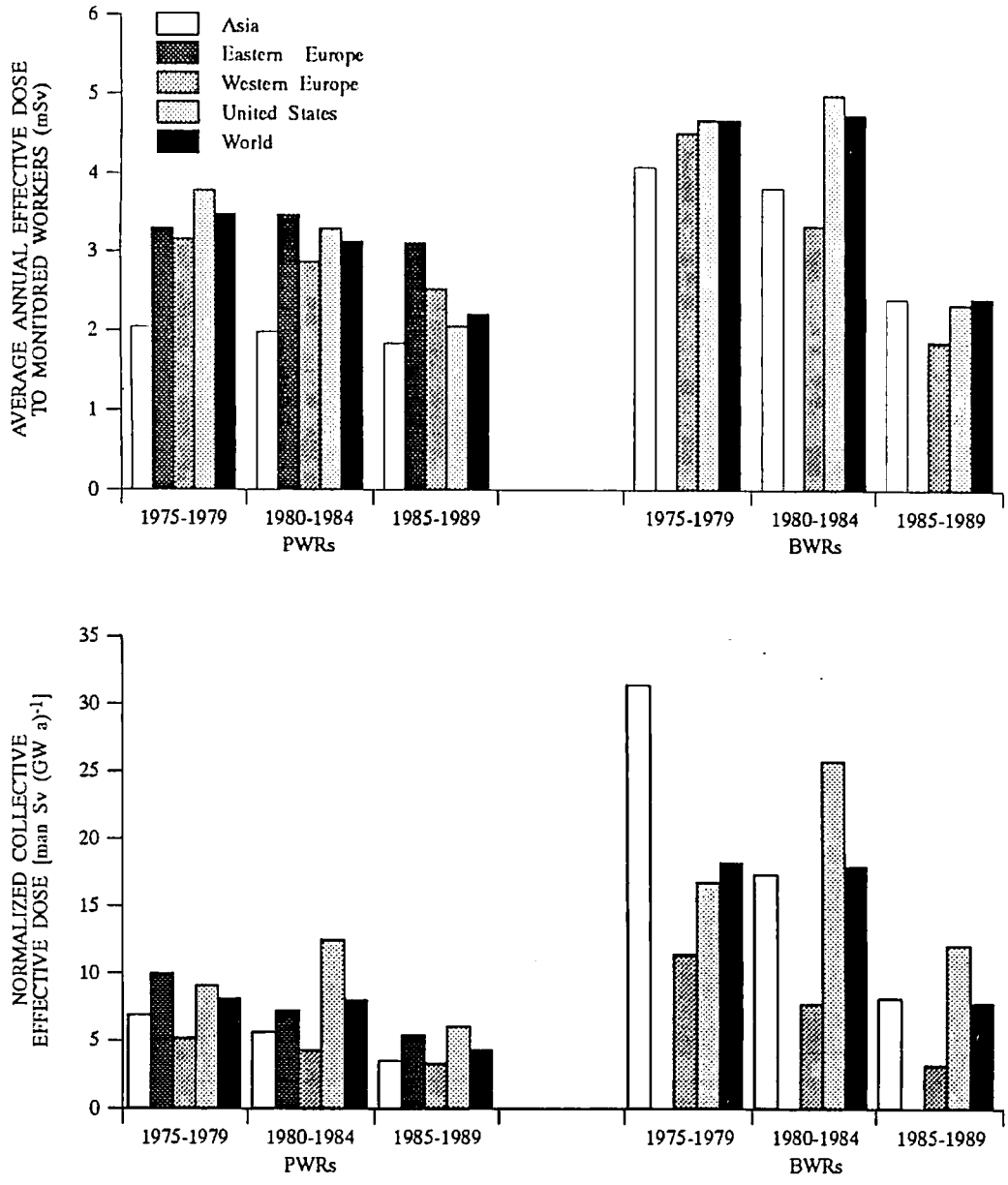


Figure VII.
Regional variations in average annual individual and normalized collective effective doses to workers at LWRs.

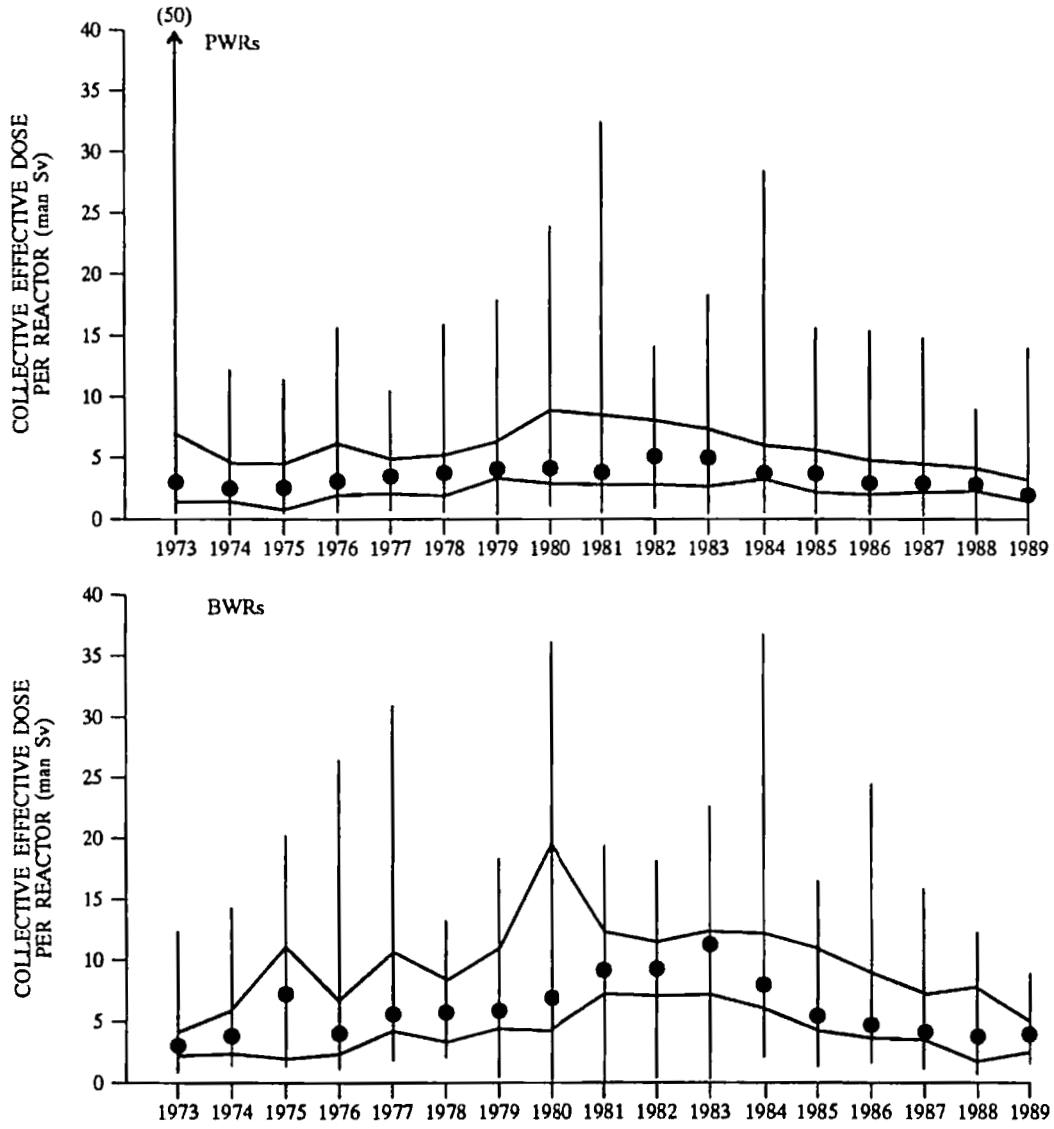
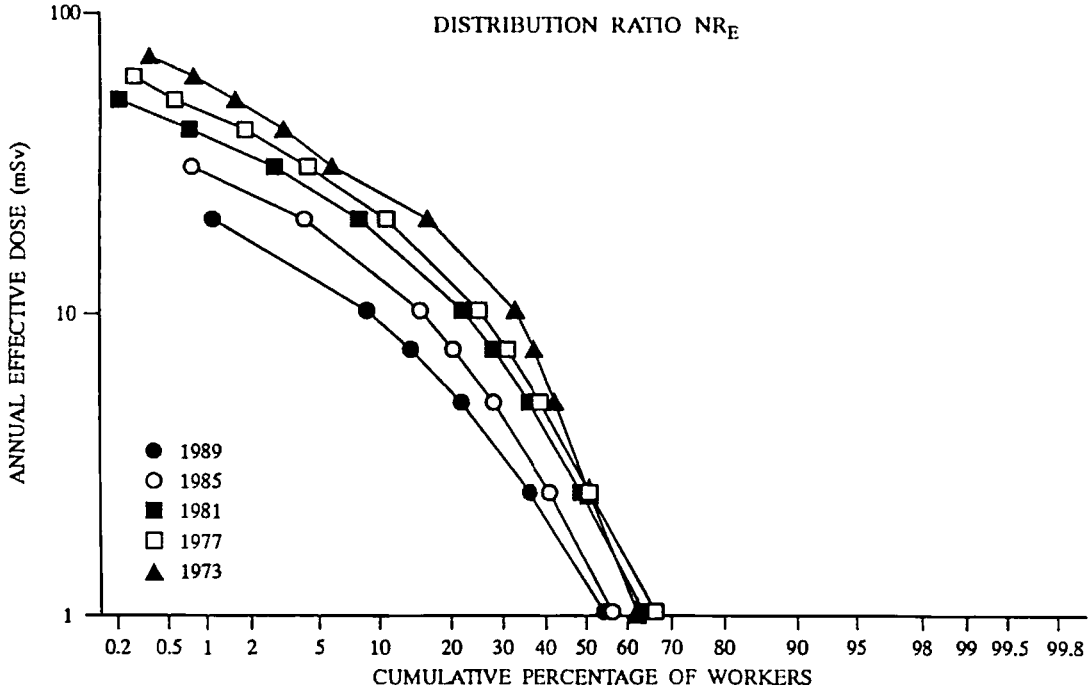


Figure VIII.
Collective dose per reactor to workers in LWRs in the United States. Median and extreme values with envelope of middle 50% values. [B3]



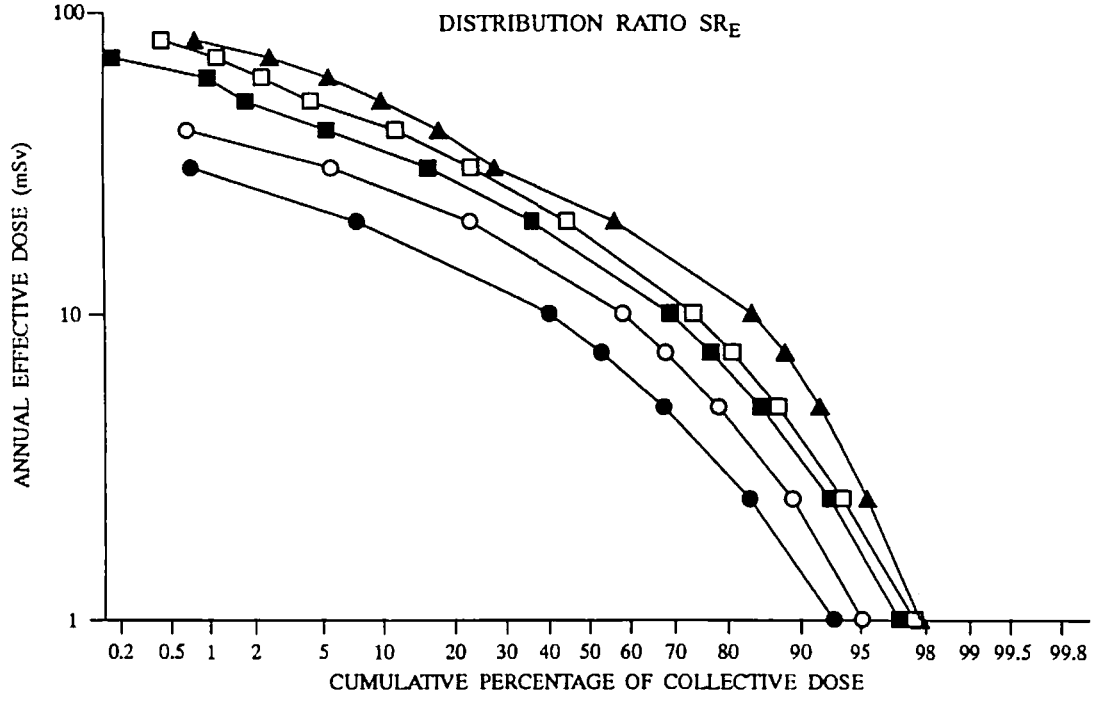


Figure IX.
Cumulative distribution of number of workers and collective dose from workers at LWRs in the United States with doses in excess of the specified values.

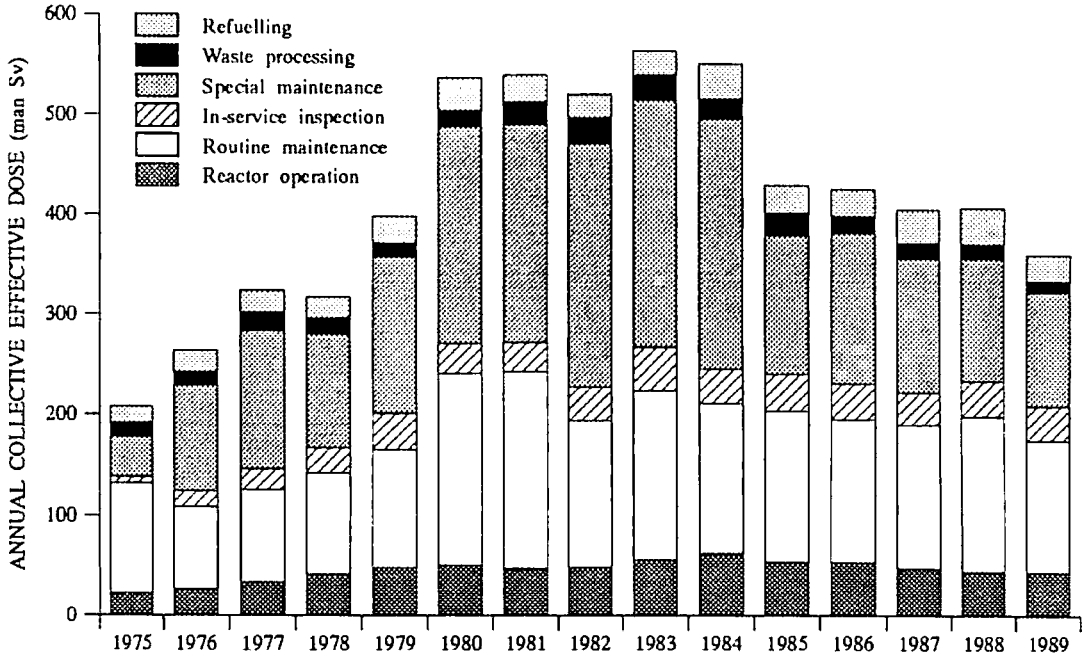


Figure X.
Distribution of collective dose among work functions for workers at LWRs in the United States.

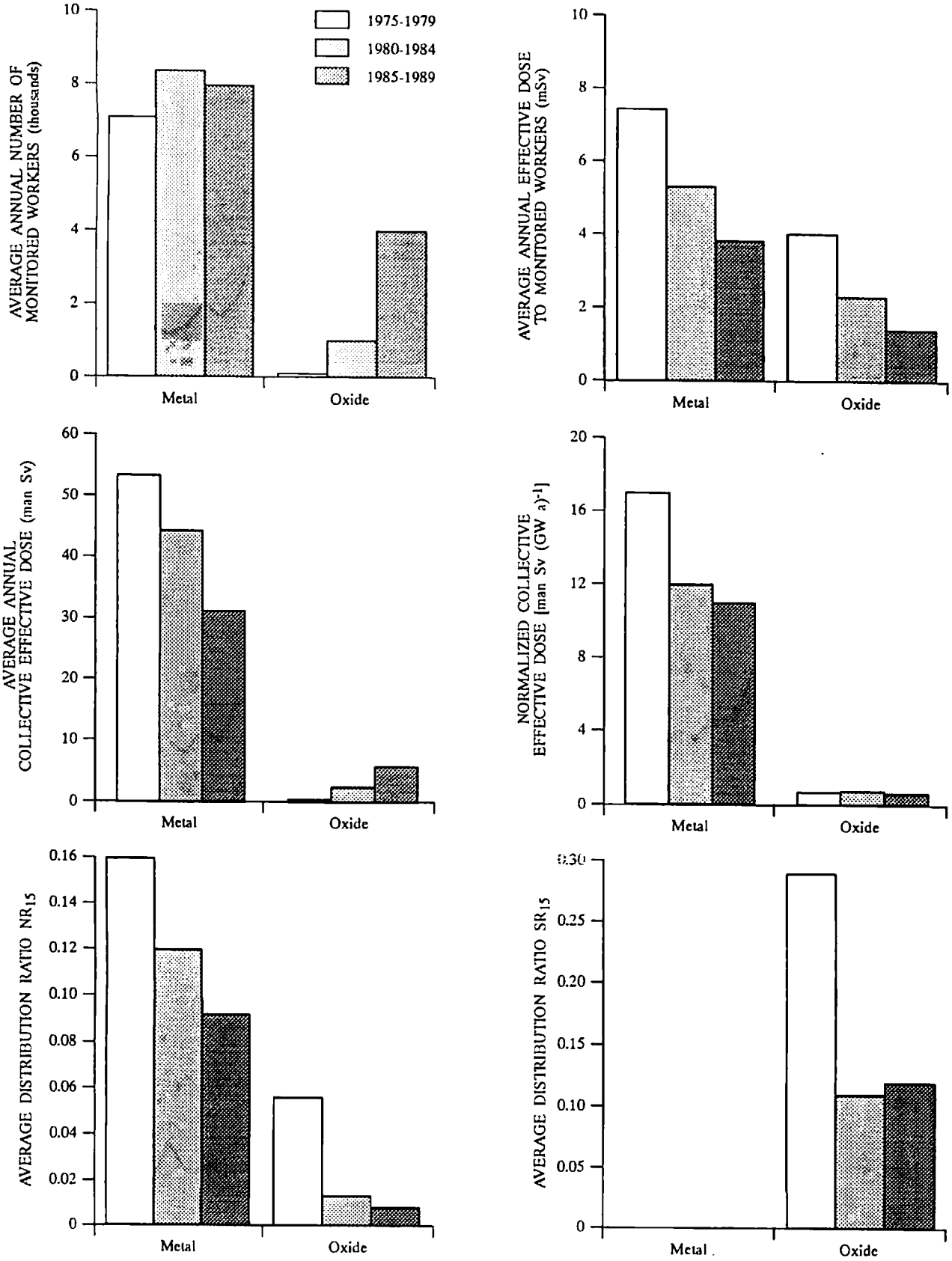


Figure XI.
Number of workers, doses and distribution ratios in fuel reprocessing.

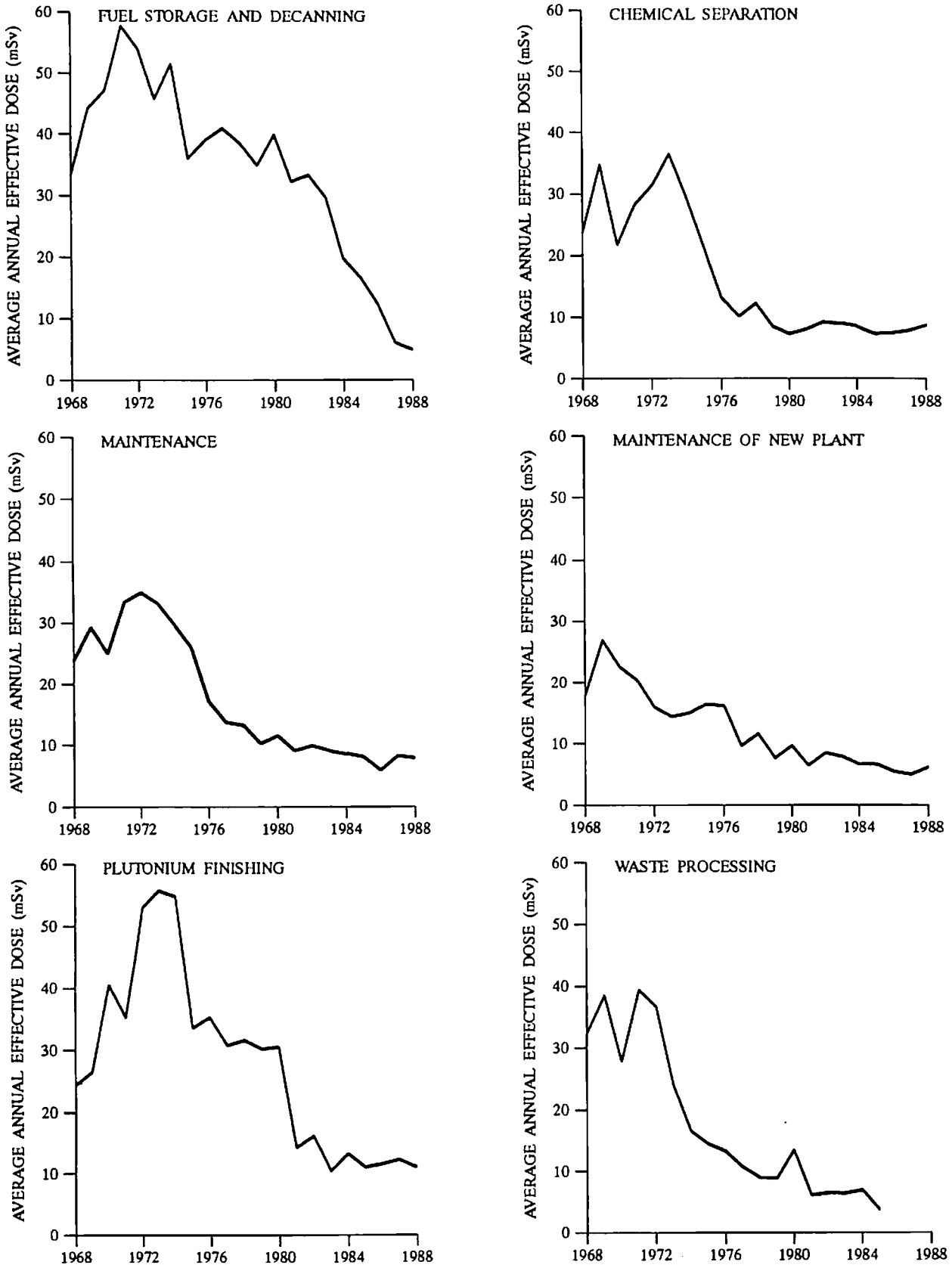


Figure XII.
Variations in average annual effective dose to groups of reprocessing workers at Sellafield, United Kingdom.
[S5]

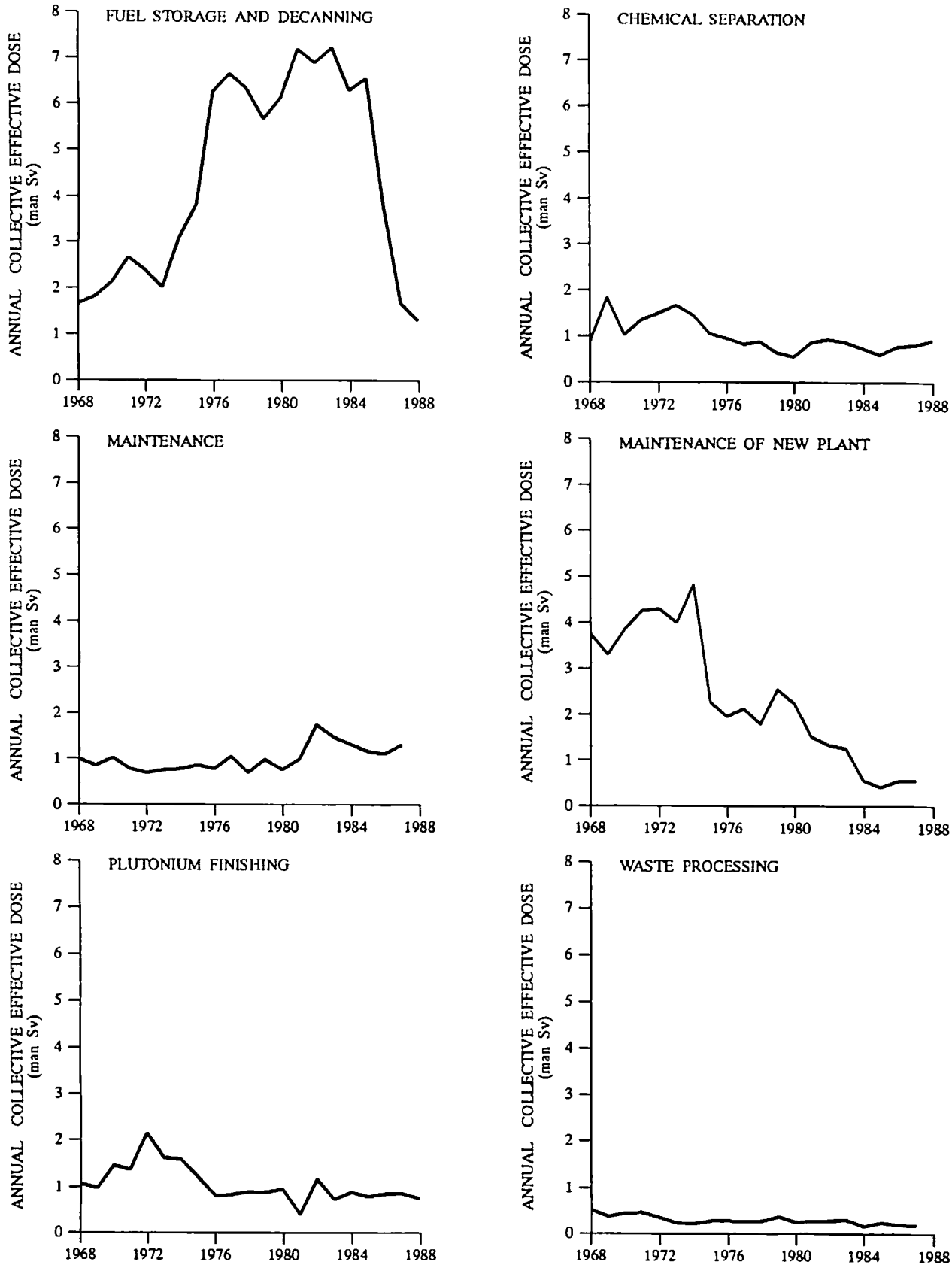


Figure XIII.
Variations in collective effective dose to groups of reprocessing workers at Sellafield, United Kingdom.
[S5]

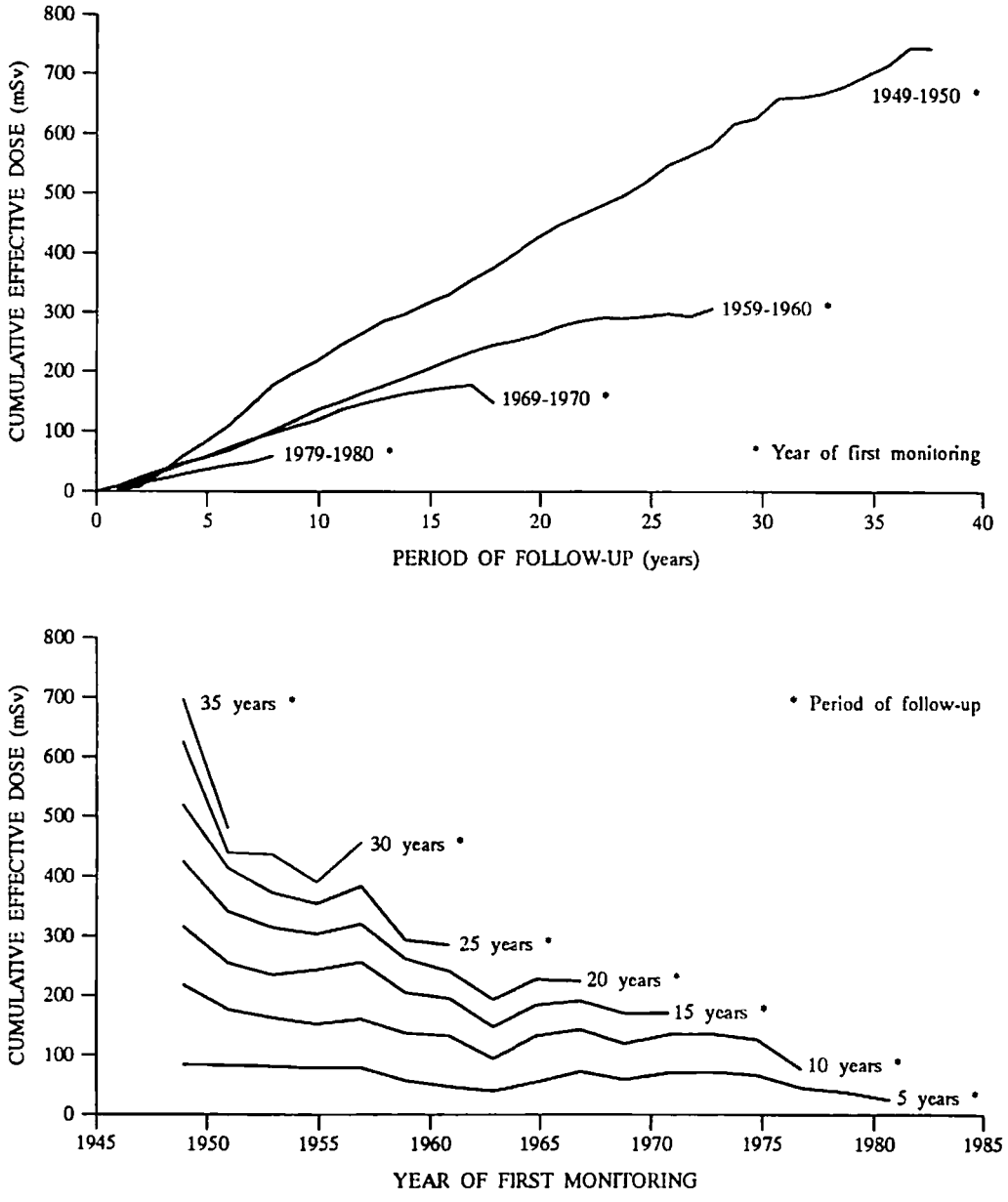


Figure XIV.
Cumulative effective dose to workers at Sellafield reprocessing plant.
[B9]

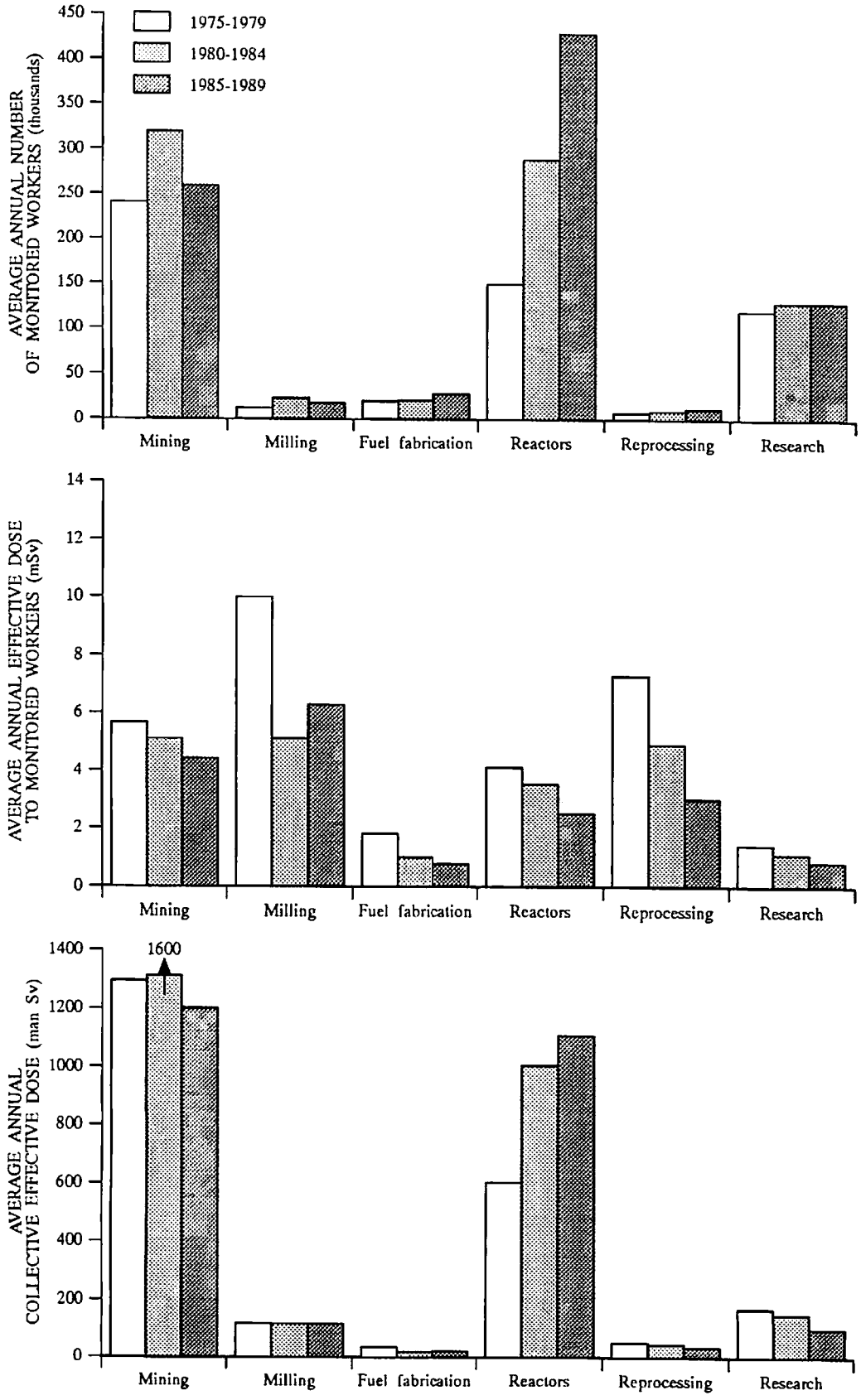


Figure XV.
Number of workers and doses to workers in operations of the nuclear fuel cycle.

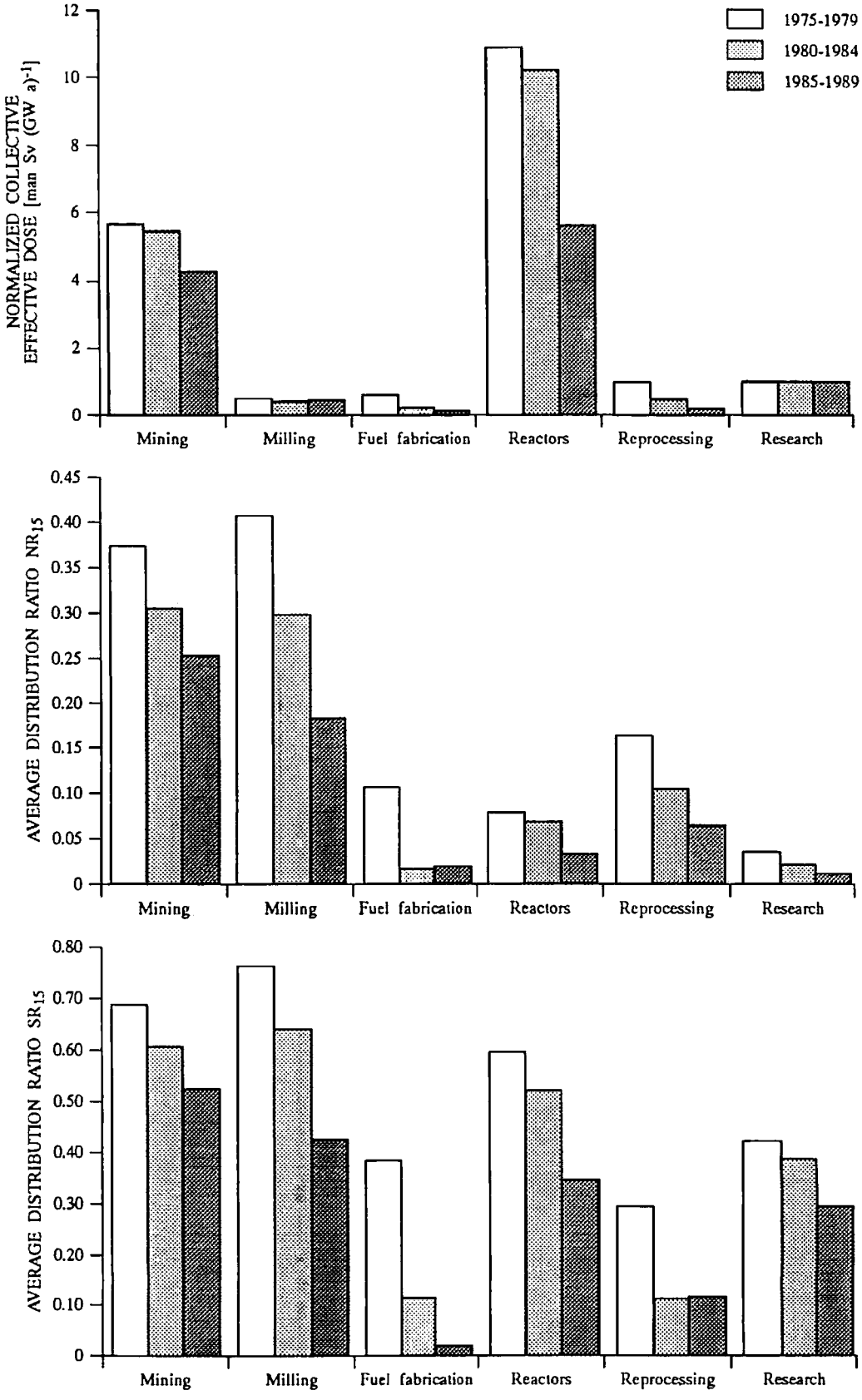


Figure XVI.
Normalized collective dose and distribution ratios for workers in operations of the nuclear fuel cycle.

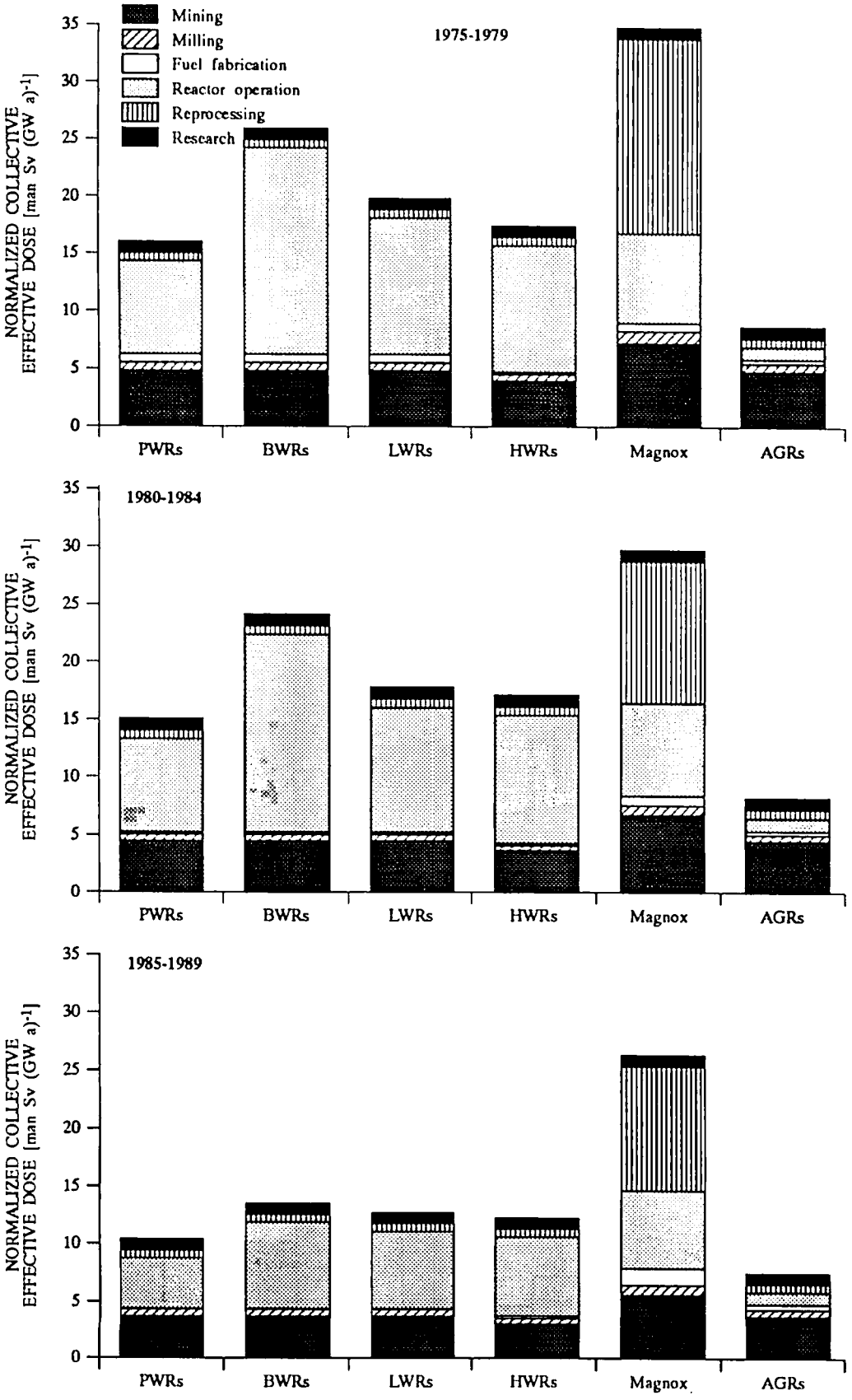


Figure XVII.
Normalized collective doses for workers in operations of the nuclear fuel cycle.

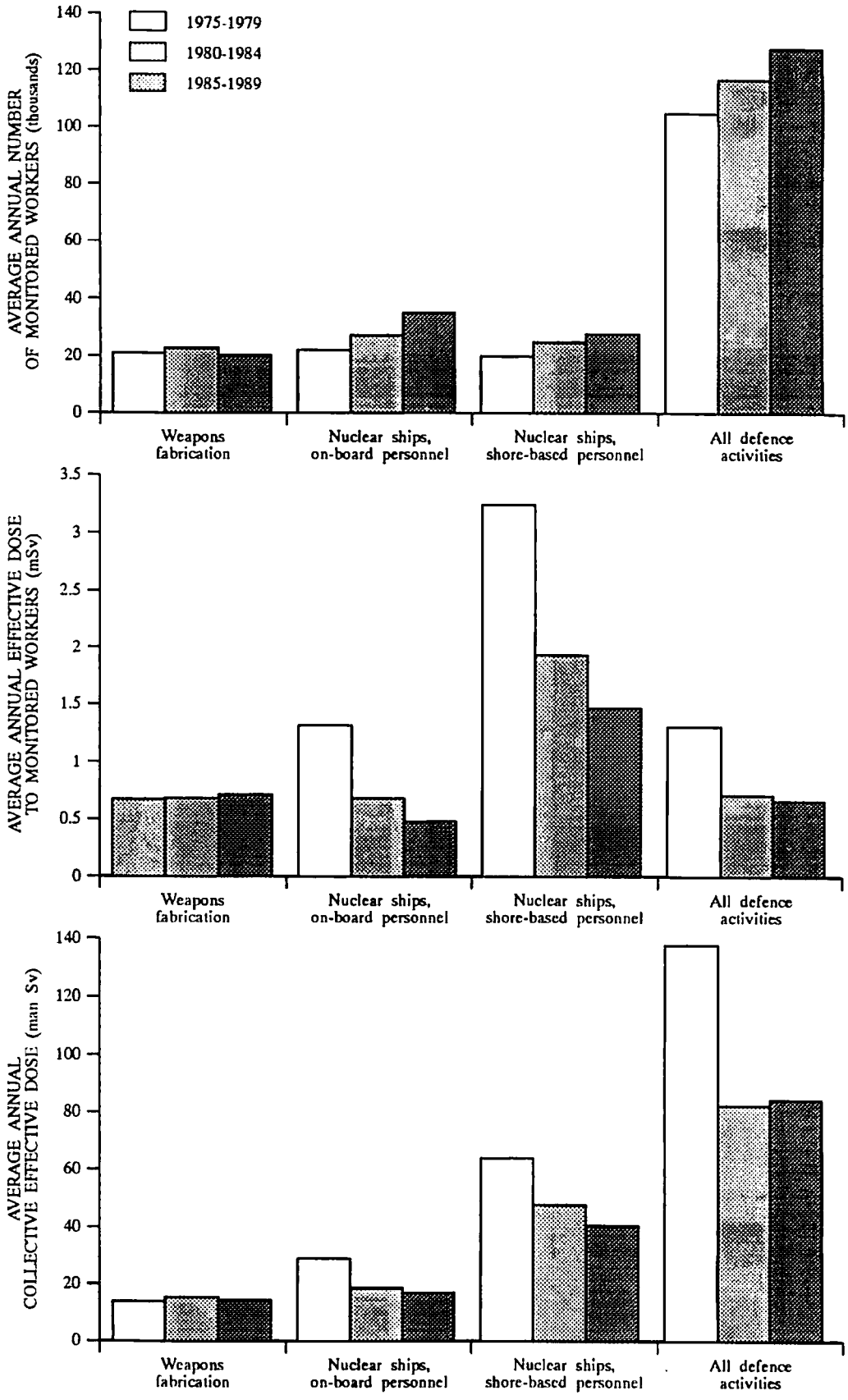


Figure XVIII.
Number of monitored workers and average annual individual and collective doses to workers in occupations involving defence activities (United Kingdom and United States only).

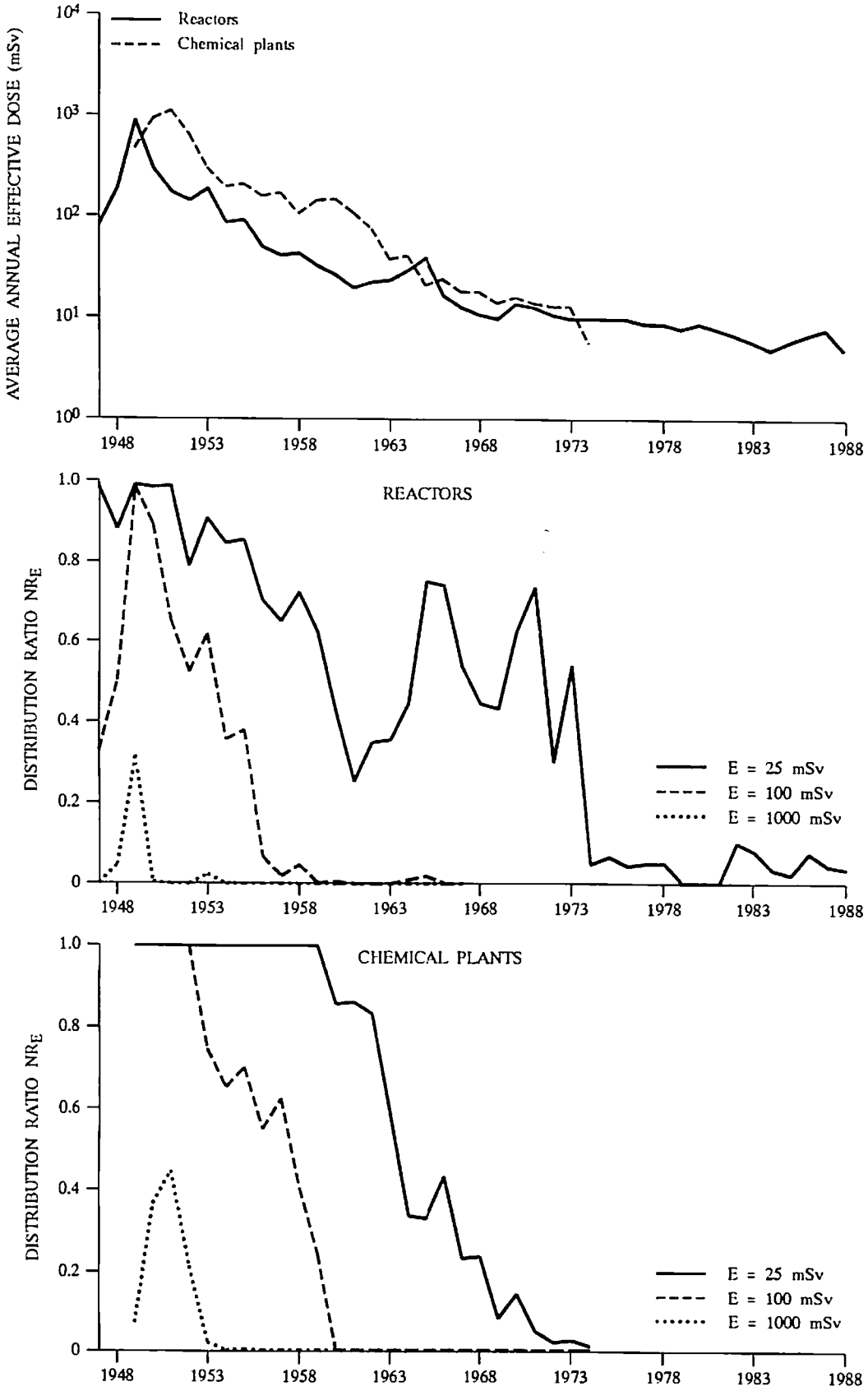


Figure XIX.
Variations in average annual individual doses and distribution ratios for workers involved in the production of weapon materials in the former USSR.

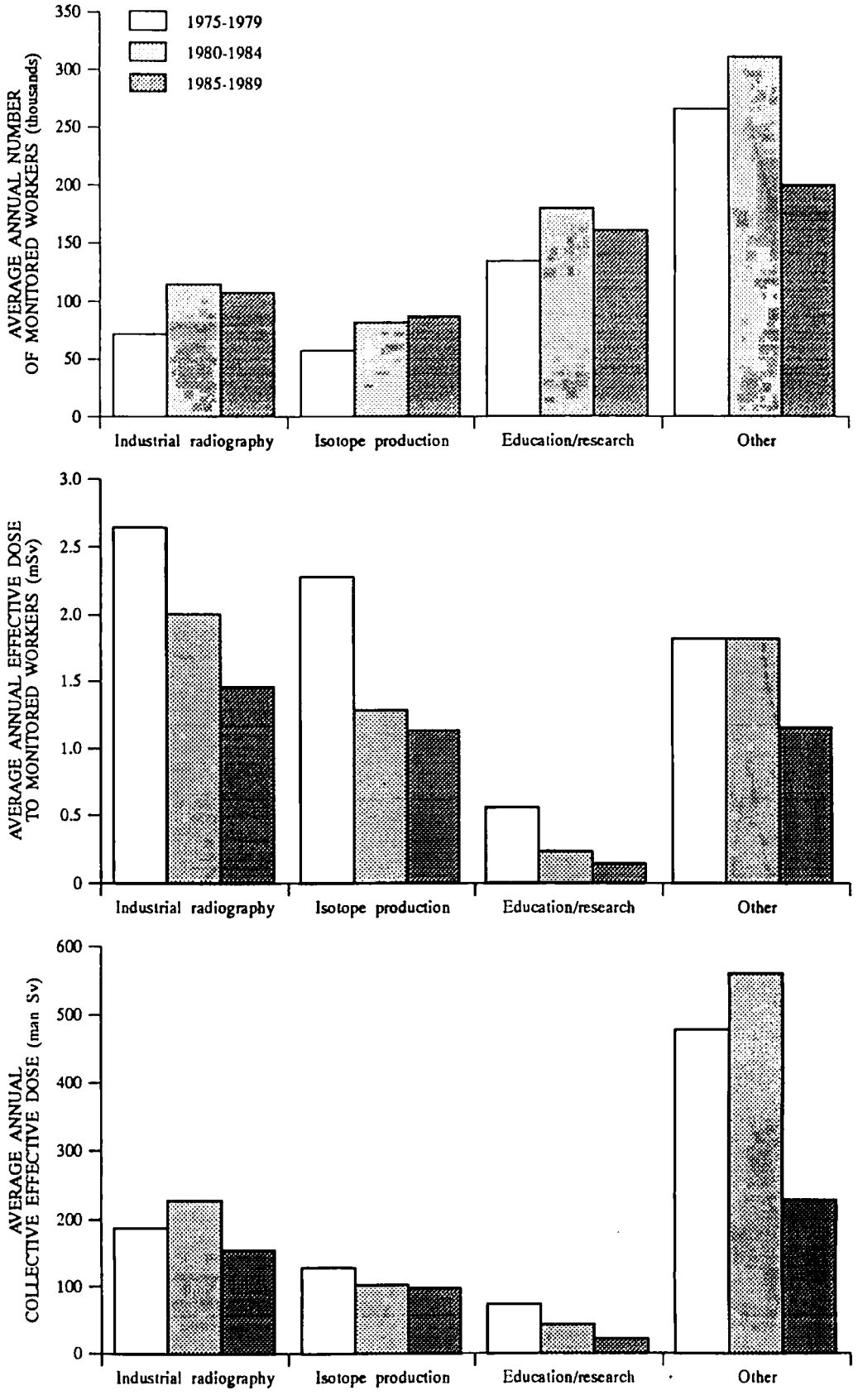


Figure XX.
Number of workers and doses to workers in occupations involving industrial uses of radiation.

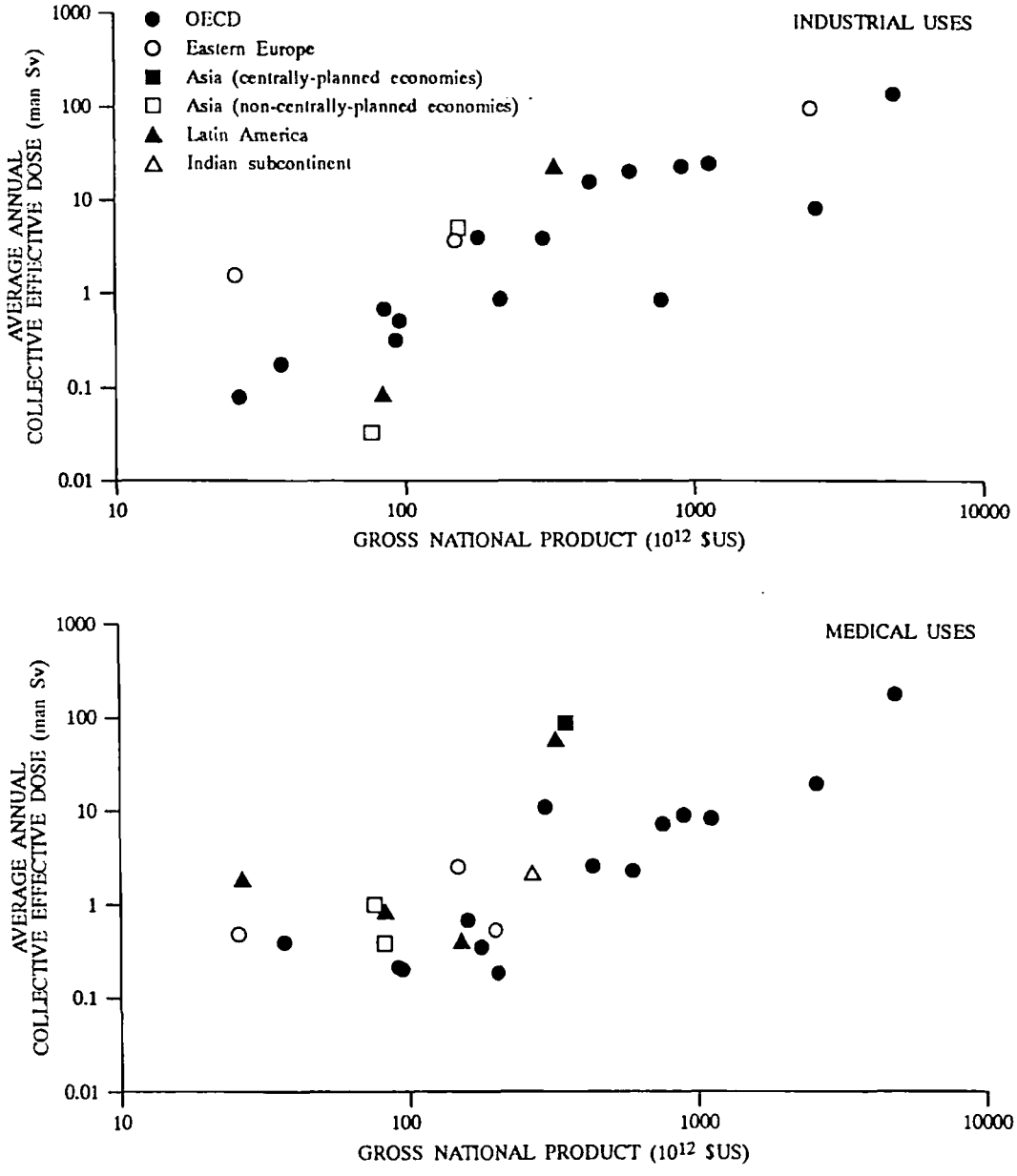


Figure XXI.
Average annual collective dose to workers in occupations involved in industrial and medical uses of radiation during 1985-1989 in relation to gross national product of countries.

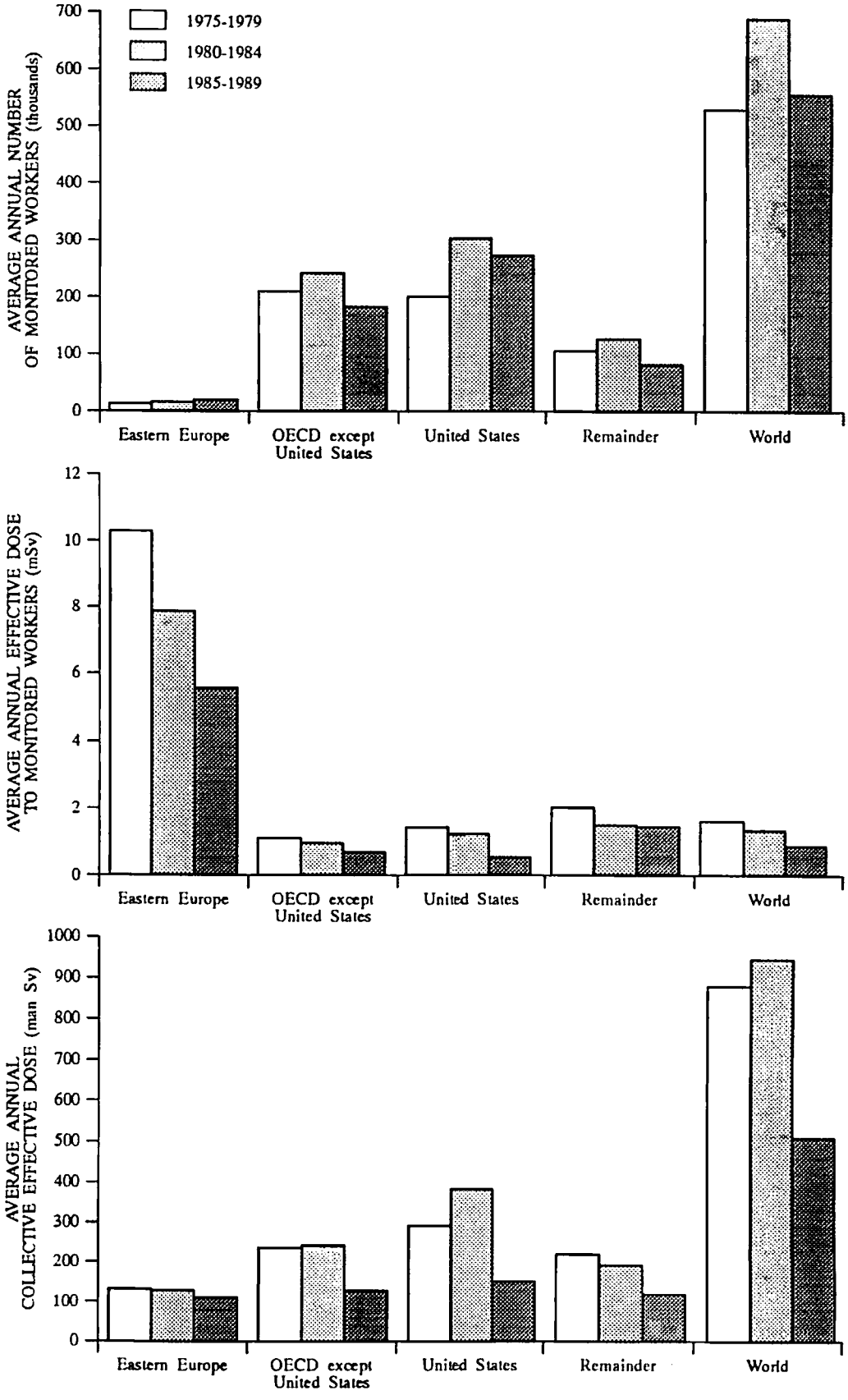


Figure XXII.
Regional data on number and exposure of workers involved in the industrial uses of radiation.

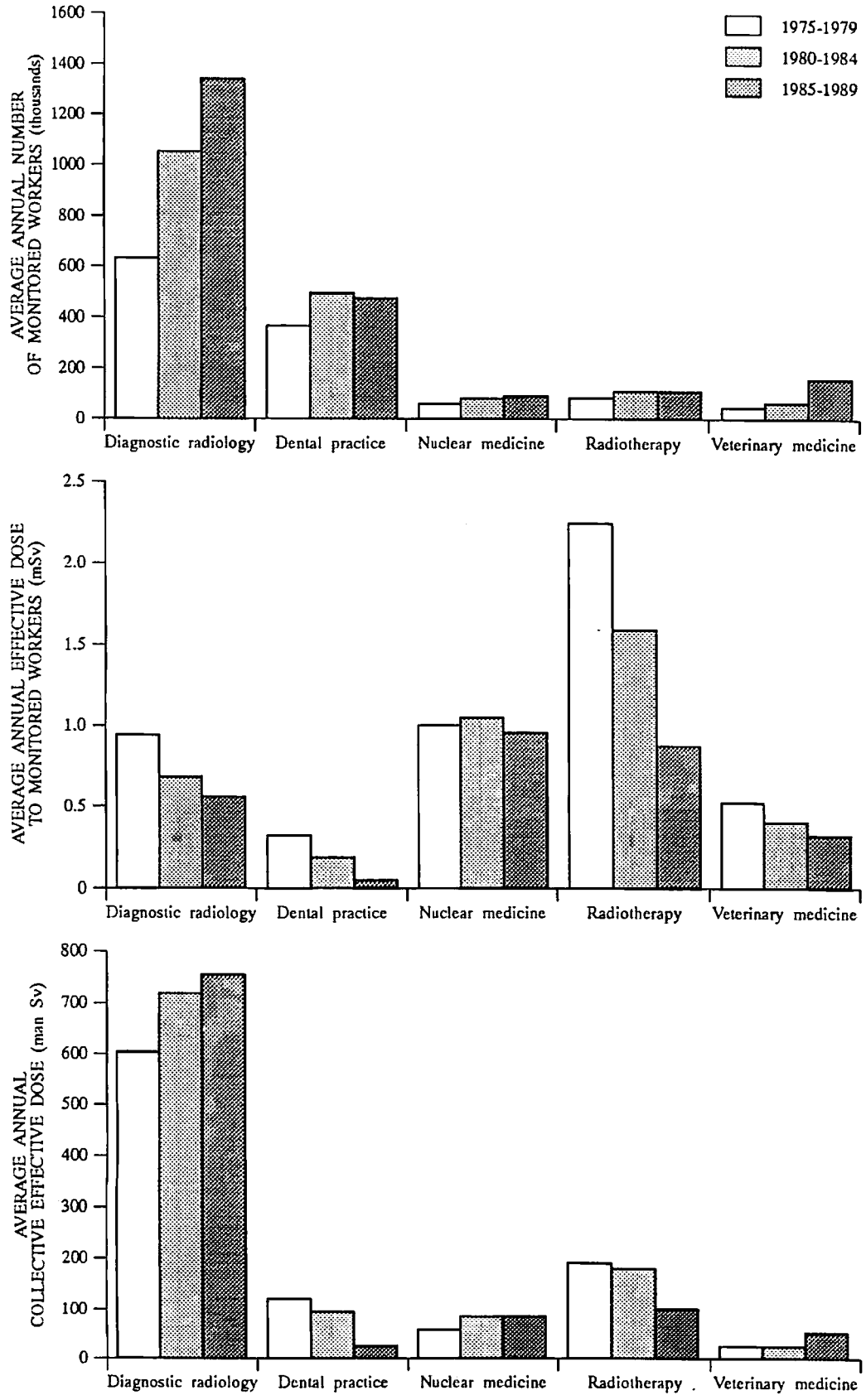


Figure XXIII.
Number of workers and doses in occupations involving medical uses of radiation.

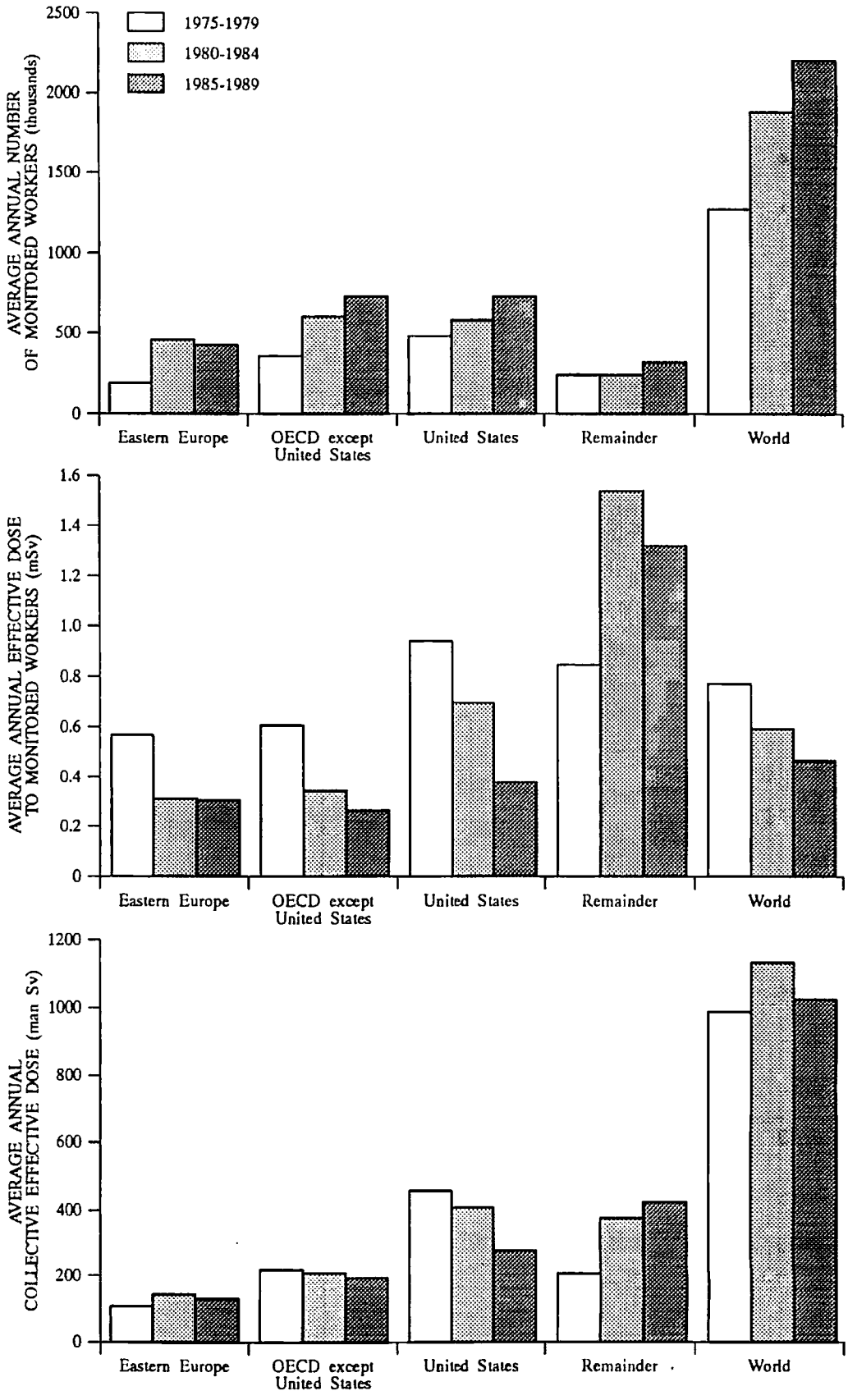


Figure XXIV.
Regional data on number and exposure of workers involved in the medical uses of radiation.

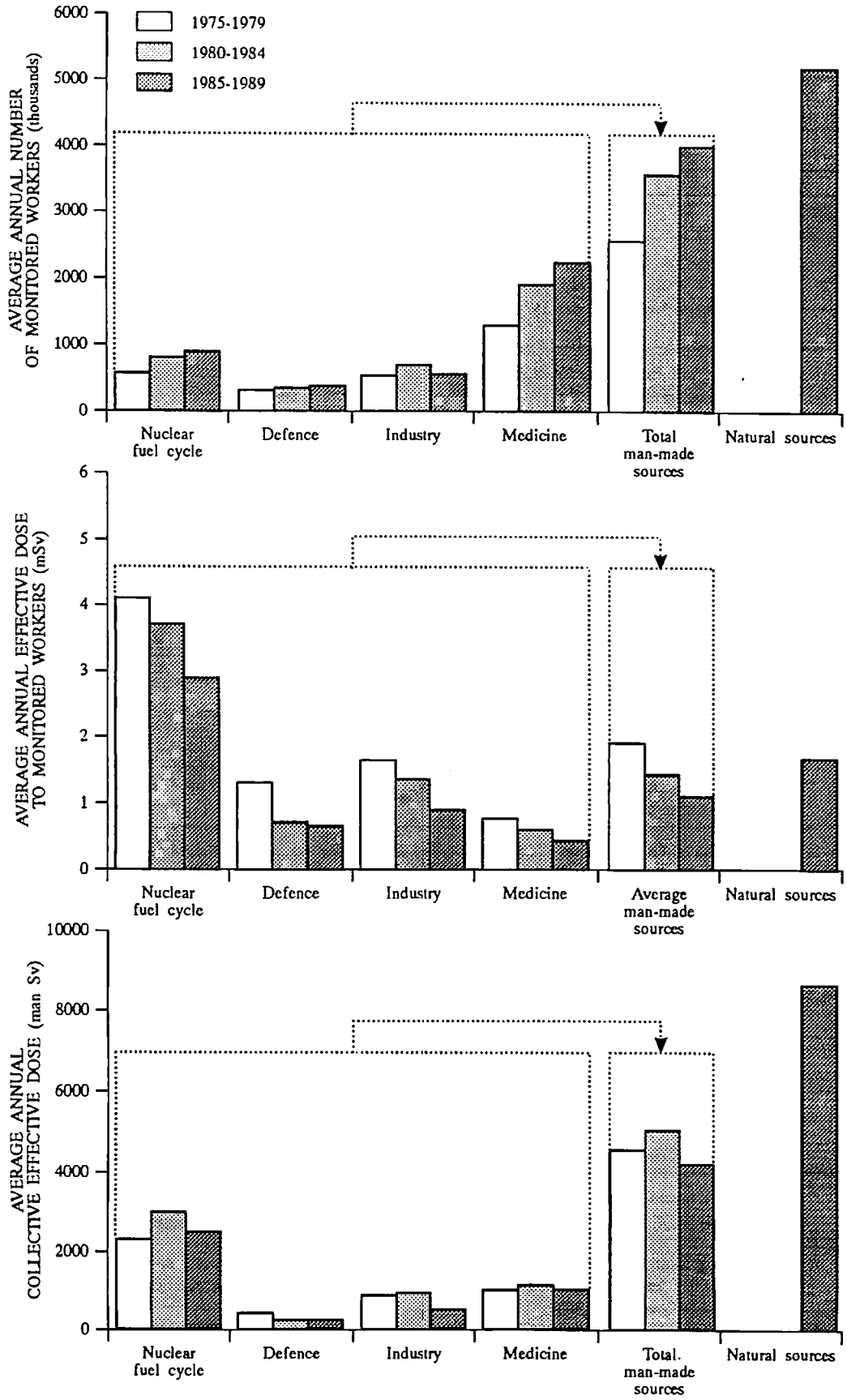


Figure XXV.
Number of workers and doses in all occupational exposures to radiation.

References

PART A

Responses to UNSCEAR Survey of Occupational Exposure

Country	*Response from*
Argentina	E. Palacios. Response to UNSCEAR questionnaire for occupational exposures incurred in industrial uses of radiation. Comisión Nacional de Energía Atómica, Buenos Aires, Argentina. (December 1990 and November 1991). E. Palacios. Response to UNSCEAR questionnaire for occupational exposures incurred in medical uses of radiation. Comisión Nacional de Energía Atómica, Buenos Aires, Argentina. (November 1991). E. Palacios. Response to UNSCEAR questionnaire for occupational exposures resulting from accidents. Comisión Nacional de Energía Atómica, Buenos Aires, Argentina. (October 1991). E. Palacios. Response to UNSCEAR questionnaire for occupational exposures incurred in medical uses of radiation. Comisión Nacional de Energía Atómica, Buenos Aires, Argentina. (February and November 1992). E. Palacios. Response to UNSCEAR questionnaire for occupational exposures incurred in industrial uses of radiation. Comisión Nacional de Energía Atómica, Buenos Aires, Argentina. (November and December 1992).
Australia	N. Morris. Response to UNSCEAR questionnaires for occupational exposures incurred in industrial and medical uses of radiation. Australian Radiation Laboratory, Victoria, Australia. (September 1991). G.C. Mason. Response to UNSCEAR questionnaires for occupational exposures incurred in industrial and medical uses of radiation. Australian Radiation Laboratory, Victoria, Australia. (December 1992).
Brazil	P. Cunha. Response to UNSCEAR questionnaire for occupational exposures incurred in medical uses of radiation. Comissao Nacional de Energía Nuclear, Rio de Janeiro, Brazil. (October 1991).
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Chile	M. Manuel Echeverria. Response to UNSCEAR questionnaire for occupational exposures incurred in industrial uses of radiation. Comisión Chilena di Energía Nuclear, Chile. (November 1990).
China	Zhang Liangan. Response to UNSCEAR questionnaire for occupational exposures incurred in medical uses of radiation. Institute of Radiation Medicine, Chinese Academy of Sciences, Tianjin, China. (November 1991).
China (Taiwan Province)	Yi-Ching Yang. Response to UNSCEAR questionnaire for occupational exposures incurred in industrial uses of radiation. Atomic Energy Council, Taipei, Taiwan, China. (October 1991). Yi-Ching Yang. Response to UNSCEAR questionnaire for occupational exposures incurred in medical uses of radiation. Atomic Energy Council, Taipei, Taiwan, China. (October 1991).

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Czechoslovakia	Z. Melichar. Response to UNSCEAR questionnaire for occupational exposures incurred in industrial uses of radiation. Nuclear Power Plants Research Institute (VUJE), Czechoslovakia. (March 1991). H. Solnická and J. Smetana. Response to UNSCEAR questionnaire for occupational exposures incurred in industrial uses of radiation. Labour Medicine Institute of Uranium Industry and Uranium Mines Management, Pribram, Czechoslovakia. (March 1991). Z. Prouza and V. Klener. Response to UNSCEAR questionnaires for occupational exposures incurred in industrial and medical uses of radiation. Centre for Radiation Hygiene, National Institute for Public Health, Prague, Czechoslovakia. (July 1992). V. Klener. Response to UNSCEAR questionnaire for occupational exposures incurred in industrial uses of radiation. Centre for Radiation Hygiene, National Institute for Public Health, Prague, Czechoslovakia. (November 1992).
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Finland	H. Hyvönen. Responses to UNSCEAR questionnaire for occupational exposures incurred in industrial uses of radiation. Finnish Centre for Radiation and Nuclear Safety, Helsinki, Finland. (November 1990 and August 1991). H. Hyvönen. Response to UNSCEAR questionnaire for occupational exposures incurred in medical uses of radiation. Finnish Centre for Radiation and Nuclear Safety, Helsinki, Finland. (October 1991).
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Germany	M. Grunwald. Responses to UNSCEAR questionnaire for occupational exposures incurred in industrial uses of radiation. Bundesamt für Strahlenschutz (BfS), Salzgitter, Germany. (September 1990 and January 1991). M. Grunwald. Response to UNSCEAR questionnaire for occupational exposures incurred in medical uses of radiation. Bundesamt für Strahlenschutz (BfS), Salzgitter, Germany. (August 1991). A. Kaul. Responses to UNSCEAR questionnaire for occupational exposures incurred in industrial uses of radiation. Bundesamt für Strahlenschutz (BfS), Salzgitter, Germany. (April and August 1991). A. Kaul. Response to UNSCEAR questionnaire for occupational exposures resulting from accidents. Bundesamt für Strahlenschutz (BfS), Salzgitter, Germany. (September 1991). A. Kaul, Arndt and Wolf. Response to UNSCEAR questionnaire for occupational exposures resulting from accidents. Bundesamt für Strahlenschutz (BfS), Salzgitter, Germany. (October 1991).

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Germany (continued)	E. Martini. Response to UNSCEAR questionnaire for occupational exposures incurred in medical uses of radiation. Land Mecklenburg-Vorpommern Landesanstalt für Personendosimetrie und Strahlenschutzausbildung-Personendosismeßstelle, Berlin, Germany. (August 1991). J. Schwedt. Response to UNSCEAR questionnaire for occupational exposures incurred in industrial uses of radiation. Bundesamt für Strahlenschutz (Dienststelle Berlin), Berlin, Germany. (May 1991). A. Kaul. Response to UNSCEAR questionnaire for occupational exposures incurred in medical uses of radiation. Bundesamt für Strahlenschutz (BfS), Salzgitter, Germany. (February 1992). A. Kaul. Response to UNSCEAR questionnaire for occupational exposures incurred in industrial uses of radiation. Bundesamt für Strahlenschutz (BfS), Salzgitter, Germany. (December 1992).
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Japan	H. Matsudaira. Responses to UNSCEAR questionnaire for occupational exposures incurred in industrial uses of radiation. National Institute for Radiological Sciences, Chiba-shi, Japan. (January and May 1991). T. Yanagi. Response to UNSCEAR questionnaire for occupational exposures incurred in industrial uses of radiation. Nuclear Safety Policy Division, Science and Technology Agency, Tokyo, Japan. (June 1992). T. Maruyama. Response to UNSCEAR questionnaire for occupational exposures incurred in medical uses of radiation. National Institute for Radiological Sciences, Chiba-shi, Japan. (June 1992).
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Spain	I.A. Calvo. Response to UNSCEAR questionnaire for occupational exposures incurred in industrial uses of radiation. Consejo de Seguridad Nuclear, Madrid, Spain. (November 1990). M.J. Muñoz. Response to UNSCEAR questionnaire for occupational exposures incurred in industrial uses of radiation. Consejo de Seguridad Nuclear, Madrid, Spain. (December 1991). M.J. Muñoz. Response to UNSCEAR questionnaire for occupational exposures incurred in medical uses of radiation. Consejo de Seguridad Nuclear, Madrid, Spain. (November 1991). M.J. Muñoz. Response to UNSCEAR questionnaire for occupational exposures resulting from accidents. Consejo de Seguridad Nuclear, Madrid, Spain. (November 1991). M.J. Muñoz. Response to UNSCEAR questionnaire for occupational exposures incurred in industrial uses of radiation. Consejo de Seguridad Nuclear, Madrid, Spain. (December 1992).
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back to first page