ANNEX D

Occupational radiation exposures

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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 $\rho \rightarrow 0$, 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

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

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} × 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 $(\text{GW a})^{-1}$ between 1975 and 1979 and increased again to about 16 man Sv $(\text{GW a})^{-1}$ 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 $(\text{GW a})^{-1}$ in the first period, decreasing to 8 man Sv $(\text{GW a})^{-1}$ in the second period and to about 6 man Sv $(\text{GW a})^{-1}$ 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 worldwide 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.