IONIZING RADIATION: SOURCES AND BIOLOGICAL EFFECTS

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on the Effects of Atomic Radiation

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NOTE

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ANNEX H

Occupational exposures

CONTENTS

Introduction

1. The Committee discussed the doses received from occupational exposure to radiation in its 1962 [U1] and 1972 [U2] reports. A detailed review of the subject was presented in Annex E of the most recent comprehensive report in 1977 [U3]. In this Annex the main intent is to focus on significant changes in the pattern of exposure which have since appeared and to present information on trends or particular causes of high exposures. It has been found useful to update the data presented in some areas, and in many cases this is done by reference to the original publications. A further object is to clarify the reasons for which the Committee requires data on occupational exposure and to suggest areas in which better data collection or analysis may be performed. The Committee has also collected and reviewed data on accidents involving the exposure of workers to substantial radiation doses. Some conclusions are drawn as to the frequency and severity of such accidents for different types of work involving radiation.

I. OBJECTIVES OF DATA COLLECTION AND ANALYSIS

2. The primary purpose of monitoring occupational radiation exposure is to provide information to be used to control the dose accumulation pattern of individuals. The information is also used to demonstrate compliance with occupational exposure limits. Neither of these require the reporting of collated data on particular work groups or sections of an industry. However, such collating and reporting is of use for radiological protection purposes such as assessing the degree to which doses within a particular industry have been reduced to levels as low as reasonably achievable [I1]. None of these purposes are those for which the Committee uses the information which has been collected and data are not therefore always presented in the form which is most useful for the Committee.

3. For particular practices the Committee wishes to assess the annual collective dose and the collective dose associated with some normalized measure so that the data from different countries and practices can be collated. This can be used to give an indication of the radiation-induced detriment to the population from each practice. The data can also be used for comparisons; for example, of the contribution of different sectors of an industry to the total radiation-induced detriment. For each type of work and for subgroups of workers within practices, the Committee wishes to assess the average level of dose and hence risk, together with the distribution of doses among the workforce. These data can be used to compare risks from radiation with non-radiation risks in the same or other occupations.

4. Data over several years can be used to assess trends in average doses, dose distributions and collective doses from complete industries or practices or from subgroups. These can be used to review whether the trends are with time, with the age of installations, with changes in technological aspects of plants or in the management of workers, with increasing size of the practice, or for some unknown reason.

5. Data on occupational exposure can also be used in principle as an input to epidemiological studies. Such data are not, however, used for this purpose by the Committee, although the Committee welcomes the opportunity to review the results of epidemiological studies carried out by others. Considerable care is needed in using the reported results of occupational dosimetry for this purpose, for the reasons pointed out in chapter II.

II. ANALYSIS OF OCCUPATIONAL DOSE DISTRIBUTIONS

A. LIMITATIONS OF THE DATA

1. The quantities measured

6. It is necessary to establish the relationship between measurements made in the radiation field by film, thermoluminescent or other personal dosimeters and the absorbed doses in the tissues and organs of the body. For relatively unshielded high energy gamma or x-radiation which does not give rise to variable absorbed dose rates throughout the body, reasonably constant relationships can be adopted. For spatially variable radiation fields, partial shielding of the body, extreme variations in distances of parts of the body from the source and similar situations, the relationships are more complex [K8, K9]. In some circumstances the complex relationships may be clarified by extra measurements and careful interpretation of measurements; these appear to be sometimes carried out, but not consistently. There are also problems peculiar to some exposures such as the orientation of the body with respect to the source.

7. As has been discussed in Annex A, for the control of dose to individuals the effective dose equivalent should be obtained by assessing doses to individual organs and tissues. In practice this is normally not done because of insufficient information on the radiation field characteristics. Monitoring badges are not generally designed to provide basic information such as the energy and type of radiation from which depth dose calculations could be carried out. In the case of non-uniform exposure of the body it is rare that sufficient information is available from monitoring devices to indicate the spatial extent and variability of the radiation field well enough to assess organ and tissue doses. These aspects have been studied in detail by Maruyama et al. [M14], who calculated organ doses and the effective dose equivalent in a phantom exposed at various orientations to radiation of different energies.

8. Dosimeters normally indicate an approximation to the absorbed dose at the surface of the body, that is to say averaged over a relatively shallow depth in tissue under a thin surface layer, together with the absorbed dose at a greater depth in tissue [M17]. Sometimes dosimeters are used for particular purposes such as to measure doses to finger tips, arms and feet. These results are often noted on individual dose records and may be used for comparison with limits on exposure of extremities. Neutron doses are recorded by special badges of a wide variety of types, intended in each case to be appropriate for the neutron energy spectrum to be encountered. Many simple neutron badges are not appropriate for measurement of intermediate energy neutrons; they should only be used if it has been demonstrated that the neutron spectrum is mainly fast or thermal.

9. The level of internal contamination is easy to determine by biological monitoring for some radionuclides (e.g., ^{3}H), but very difficult for others (e.g., ^{239}Pu), especially at long times after intake or in cases of multiple intake. Biological monitoring is taken to include excreta monitoring and external counting. Previously, in most organizations, attempts were made to estimate body content as a fraction of the Maximum Permissible Body Burden and the results of monitoring were expressed in these terms. With the change by ICRP to Annual Limits of Intake there is likely to be a corresponding change in attempting to estimate and report annual intakes and committed doses. One difficulty in compiling statistics is that reporting levels for internal contamination vary widely.

10. The Committee has previously adopted the convention that all numerical results reported by monitoring services represent the average absorbed dose in the whole body and recognized that it is almost always the reading from the dosimeter which is reported, without consideration of its relationship to the absorbed dose in the body. This is still regarded as a reasonable convention as most data are on external exposure of the whole body to ionizing photon radiation of moderately high energy for which the quality factor is one. The same convention has again been adopted in this Annex. In situations where exposure of the body may be non-uniform, especially in medical practice, it may be misleading to average across different types of work as the relationship between reported dosimeter reading and average absorbed dose in the whole body will not be constant. Such variations will be noted when information is available.

2. Monitoring and dose recording practice

11. The number of workers subjected to different levels of monitoring is a function of management and enforcement agency decisions on the likelihood of exposure at or above different levels. It is not therefore consistent within an industry or in a given country, and certainly not between industries or between countries. The ICRP [I1, I2] recommends that in cases where it is most unlikely that annual doses will exceed three-tenths of the dose limit, individual monitoring is not necessary, although it may sometimes be carried out as a method of confirming that conditions are satisfactory. 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 such a criterion. Having been issued, even trivial doses from the devices are aften reported, despite the ICRP recommendation of a recording level of one-tenth of the annual limit. There is some discrepancy in the treatment of external and internal radiation, which may be because monitoring for internal irradiation is only undertaken in those few circumstances where there is a clear need. Internal doses can be assessed indirectly by monitoring activity concentrations in air, but there is considerable uncertainty over the relationship between the measured concentrations and the retained body content. The result of such monitoring is not always transferred to individual dose records.

12. Difficulties such as these contribute to the problem of defining the number of exposed workers and may lead to differences in reported average doses. The Committee feels that whether the reported data are for all of those monitored and the basis on which they were selected for monitoring should be clarified. How dose estimates are obtained for those individuals who are not monitored, e.g., air crew, underground miners, should also be made clearer. It is assumed throughout that natural background radiation has been subtracted from the reported results and that medical doses are not included. Even medical exposures required as a condition of employment or given as a result of employment are not included.

13. There is also some variation in the procedures used for reporting dosimeter readings which are less than the minimum detectable level for the particular dosimeter. These may be entered into the records as either zero or the minimum level. Due to difficulties of this type the Committee has developed certain analytical procedures, described later, to extract information from dose distributions. More information on precise procedures used in reported results would be useful.

3. Notional doses

14. When dosimeters are lost, or the readings are otherwise not available, it is a common procedure for compliance with legal or statutory requirements to assume that the individual exposed has received the appropriate proportion of the annual authorized limit for the period for which results were lost. However, this procedure can distort records, particularly if large numbers of dosimeters are lost within a particular occupational group. The Committee therefore would find it most useful if doses could be reported with an indication of the number of notional doses, the procedure adopted and, if possible, a revised dose estimate with the notional doses substituted by a dose calculated from the average dose over the remainder of the year for each individual. This procedure is only appropriate in routine situations; when high exposures are suspected, such as after an accident, then biological monitoring may be more appropriate.

B. CHARACTERISTICS OF DOSE DISTRIBUTIONS

15. Dose distributions are the results of many constraints imposed by the nature of the work itself, by the 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 in particular act as a feedback mechanism which applies especially as individual doses approach the annual dose limit, or some proportion of it, in a shorter period of time. Individual doses may be reduced to lower levels in some circumstances by management decisions but, unless changes are made to the job or the working conditions, more workers will be needed to carry out the job and the collective dose will generally increase [G1, H1].

1. Example of a dose distribution

16. In order to clarify the discussion on the characteristics of dose distributions the Committee has found it useful to take an example of a dose distribution which exhibits many of the characteristics of interest. This

example, which is given in Table 1, is not an actual distribution, although it is similar to those distributions found for workers on light water reactors (LWRs), in fuel reprocessing, in research and development, in industrial radiography and in luminizing. It must be emphasized that this is not a typical or an optimum distribution; it is no more than an illustrative example.

17. In Annex E of the 1977 report, 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 on a probability axis against the logarithm of dose. This procedure was referred to in Annex E of the 1977 report as a "log-probability plot" and will be used again in this Annex. The log-probability plot of the data from Table 1 is shown in Figure I. The straight line in the Figure is the result of a least squares fit to the points up to and including the point at 15 mGy. The results calculated from this fit are

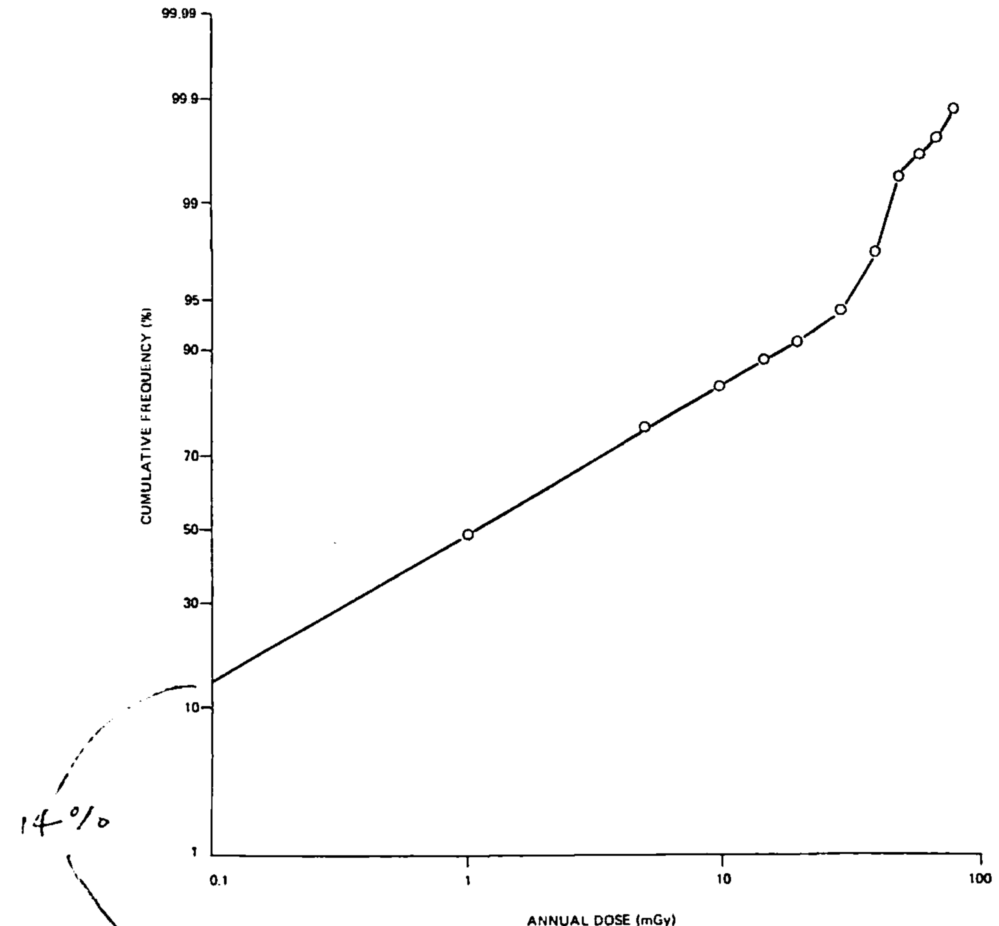

Figure I. Example log-probability plot of data from Table 1

compared in Table 1 with those obtained from simple arithmetic mean doses in each range.

18. Table 1 and Figure I show some of the characteristics of interest and that there is some lack of clarity of the number of workers taken to be unexposed. From the log-probability plot it is possible to obtain the collective dose as described later. The average dose is of course related to the number of workers so that if the collective dose is extracted from the distribution using a fit to the log-normal if appropriate, then the average dose is determined by the number of workers. The main point of the log-normal fitting is to make a better allowance for the skewness of the distribution towards zero doses than using the mid point dose in the lowest dose band. This is illustrated in Table 1.

19. In principle, if the dosimetry data are reported with doses below the threshold of detection as zero, then addition of any arbitrary number of unexposed workers will not affect the collective dose, nor the average dose to those workers actually exposed. However, it will clearly increase the total number of workers considered and decrease the average dose based on that total. There is no precise method to determine the number of unexposed workers, but it is possible to calculate the number of workers in the sample below any arbitrarily selected annual dose level from the log-normal fit. For example, using the distribution in Table 1, if this level is taken as 0.1 mGy, the number found from the log-normal fit to receive less than 0.1 mGy is 140 people. Procedures of this type have not been used in this Annex but the determination of the numbers of exposed and unexposed workers merits further consideration, as has been done in recent reports by the United States Nuclear Regulatory Commission [B17, B18]. Drexler et al. [D9] have assessed the average doses to all those monitored and to those with measurable doses for a number of occupations; the ratio of the two averages ranges from about 1.5 to 20 for different occupations.

20. Another characteristic which may be seen in Figure I is the deviation from log-normal as the doses approach 50 mGy per year, the currently recommended dose limit for occupationally exposed workers [I1],

which has become progressively observed as an annual limit during recent years. This means that the log-normal is not a complete description of the dose-frequency characteristics. Since there are likely to be only a few people in the higher dose ranges it is reasonable to request that those reporting data give collective doses based on summation of individual results at higher individual doses. It would also be helpful to give the number of workers in individual dose bands which are rather narrower than has been the practice. These data would clarify the effects on the distribution of dose limits; and if such reporting were routine then all the required data on the upper end of the distribution could be derived directly without introducing any further assumptions or approximations. It has been suggested by Kumazawa and Numakunai [K12] that the control of doses approaching the dose limits leads to a normal distribution in the higher dose range; this presumption can be used to carry out analysis as a hybrid normal/log-normal distribution.

21. A characteristic of the dose distribution identified by the Committee in 1977 [U3] as being of interest was the fraction of the collective dose delivered above a given annual dose level taken in that report as 15 mGy. This fraction is plotted in Figure II as a function of the annual dose level for the example distribution of Table 1. It clearly shows the effect of efforts to keep doses within the dose limit.

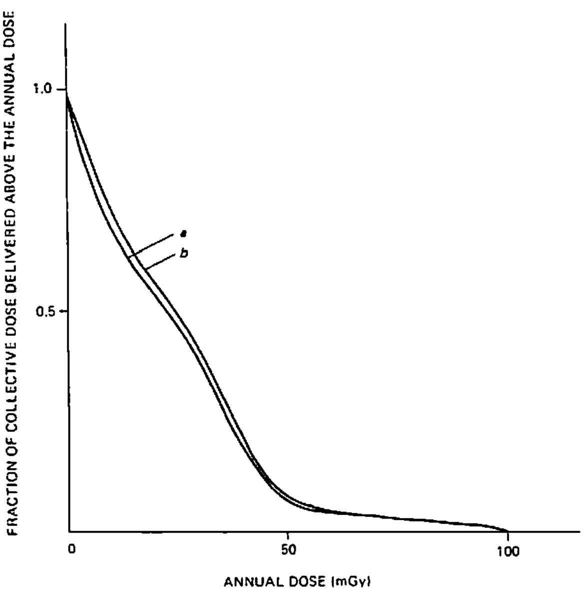

Figure II. Example of the fraction of collective dose above a given annual dose level (data from Table 1)

a Calculated as the number of workers in each range multiplied by the mid-point dose.

b Calculated from the log-normal fit below 15 mGy.

22. The three characteristics of the dose distribution previously identified by the Committee as of interest still seem to describe the distribution in a useful fashion. These characteristics are:

(a) The annual average dose, $\overline{D}$, which is related to the average level of individual risk. For consistency, in this Annex the average is generally calculated for all individuals monitored in a given occupational group.
(b) The annual collective dose, M, which is related to the impact of the practice.
(c) The ratio of the annual collective dose delivered at individual doses exceeding 15 mGy per year to the total collective dose, MR, which is related to the proportion of workers exposed to higher levels of individual risk.

23. These characteristics may be obtained for any form of the dose distribution, whether or not it exhibits a log-normal response over some part of the dose range. They should be obtained from the detailed basic data on the dosimetry results and reported with any collated reports of the data where possible. The definitions of the annual collective dose, M, are as follows:

$$M = \sum_{n=1}^{N} D_n \qquad (1)$$

where N is the total number of workers, D_n is the annual absorbed dose received by the nth worker. In practice M is often calculated from collated dosimetry results using the alternative definition

$$M = \sum_{0}^{\infty} N_i \overline{D}_i \qquad (2)$$

where N_i is the number of individuals in the ith absorbed dose range for which $\overline{D}_i$ is the mean annual absorbed dose. In some circumstances, because in general the dose distribution is skewed towards low doses, use of the mid-point dose in a range as an approximation to $\overline{D}_i$ will lead to an overestimate of the collective dose. For typical dose ranges the over-estimate is thought to be less than 10% [B22]. The annual average absorbed dose, $\overline{D}$, is given by

$$\overline{D} = \frac{M}{N} \qquad (3)$$

where N is the total number of workers monitored. The annual collective dose distribution ratio, MR, is defined as

$$MR = \frac{M(>15)}{M} \qquad (4)$$

where $M(>15)$ is the annual collective absorbed dose delivered at annual individual doses exceeding 15 mGy. This should, where possible, be calculated from the summation of individual doses.

24. Normal ranges for similar characteristics were given in Annex E of the 1977 report [U3]. These were intended to highlight those distributions with values either above or below the normal range, which could be used for decisions on dosimetry practices or causes of exposure. The normal ranges for the characteristics used in this report which replace those in the 1977 report, are:

$\overline{D}$ from 1 to 10 mGy
MR from 0.05 to 0.5

2. The reference distribution

25. The Committee in Annex E of the 1977 report [U3] defined a reference distribution such that:

(a) The distribution of annual doses is log-normal;
(b) The mean of the annual dose distribution is 5 mGy;
(c) The proportion of workers exceeding an annual dose of 50 mGy is 0.1%.

26. It was not the intent of the Committee that this reference distribution be considered an ideal or optimal distribution of doses and it should not be so interpreted. The distribution was only intended to give some basis for intercomparison and in so far as the parameters were defined ab initio it was artificial. It also did not show the common characteristic noted in Section B.1 of deviation from the log normal. This reference distribution, together with the observed range of parameters in the 1977 report, was used to obtain a normal range for the parameters of interest for dose distributions. One of the parameters, the proportion of the collective dose delivered at annual individual doses exceeding 15 mGy, was normalized with respect to the reference distribution. As has been pointed out [B17, B19, K10, K11], there were some errors in the normalization procedure used to obtain the parameter Ω, (the ratio of the fraction of the collective dose due to annual doses above 15 mGy for the observed distribution to the fraction for the reference distribution) the main result of which is that the fraction of the collective dose due to annual doses above 15 mGy for the reference distribution should have been 0.202 rather than 0.310. The normal ranges for the parameters given in the 1977 report were: $\overline{D}$ from 1–10 mGy; Ω from 0.1–2.0 (if Ω is recalculated correctly the range would be from 0.15 to 3.0).

27. In view of the difficulty over calculational inaccuracies and because the attention which has been paid to the reference distribution was more than anticipated, it was decided, as noted in the previous section, to revert to a basic characteristic concerned with each distribution. This characteristic is the fraction of the collective dose delivered at individual doses exceeding 15 mGy. The range for this characteristic, MR, which would correspond to the range used in the previous report for Ω, is from 0.03–0.6; however, it has been decided to adopt the normal range given earlier of 0.05–0.5 for MR.

3. Techniques for analysis of dose distributions

28. If the complete data on annual individual doses within a distribution were available, together with the treatment used for reporting dosimeter readings below the detection threshold and the treatment used for reporting notional doses, then it would be straightforward to extract the characteristics required by the Committee. However, data are normally reported grouped into dose ranges of different widths, often without such additional indications. The 1977 report used the observation that the distribution is often log-normal, especially for doses which do not approach the dose limit [B20, S18]. Where the required information cannot be extracted directly from the reported results, a log-normal fit to the appropriate part of the distribution is therefore used to extract the collective dose, and the fraction of the collective dose delivered in different individual dose ranges. This procedure is used, where possible, to assess collective doses to the large numbers of people in the lowest dose band who may receive very low or zero dose but are given dosimeters for administrative reasons.

29. A variable D is said to be distributed log-normally if the values of $y = \ln D$ are distributed normally. The mean, median and mode of the distribution of y is μ ; the variance of the distribution is σ^2. The probability that a value of D will lie between D and D + dD is [F5]

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

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

$$M_D = \frac{N_D}{\sqrt{2\pi}}e^{\left(\mu+\frac{\sigma^2}{2}\right)}\int_{-\infty}^{t} e^{-t^2/2}\,dt \qquad (6)$$

where the substitution variable $t = \frac{(\ln D-\mu-\sigma^2)}{\sigma}$, and N_D is the number of people receiving annual doses up to D; this is usually determined directly from the original data. The substitution using t is made to render M_D in the form shown since tabulations of the cumulative normal distribution function are readily available. The choice of the appropriate value of D for each distribution is made by inspection of the data plotted on log probability graph paper; very often 10 or 15 mGy is a convenient value.

30. Graphical techniques are of sufficient accuracy for analyses of dose distributions and are described both in standard texts [F5] and in the context of occupational dose distribution analysis [B20]. If a straight line is fitted by eye or by the method of least squares to the plot of the cumulative frequency versus ln D, then the value of D is $(\mu-\sigma)$ at a cumulative frequency of 15.87% and $(\mu+\sigma)$ at a cumulative frequency of 84.13%. M_D can then be obtained from standard tabulations.

31. An alternative procedure used for the analyses in this Annex for which sufficient data were available is to apply the method of least squares to obtain the equation for the best fit line up to the annual dose, D, chosen from inspection of the plot, and then a numerical integration to obtain the collective dose up to the value D, and up to 15 mGy if this was equal to D. The collective dose in the ranges above D is obtained from the original data using either the number in each range and the mid-point dose or the actual doses in higher ranges if provided. If D is less than 15 mGy, then M_{15} is calculated from

$$M_{15} = M_D + M_{(15-D)} \qquad (7)$$

where M_D is obtained from the least squares fit and $M_{(15-D)}$ from the original data.

32. Recently some analyses of distributions as a combination of log-normal and normal distributions have been made [K12]. The hybrid log-normal is derived from the log-normal by including a feedback mechanism which relates control of future doses to the previous cumulative dose. As this includes constraint functions which appear to apply rather generally it is probably a better way to represent observed distributions. However, it has not yet been developed and utilized sufficiently for use in this report.

33. It must be emphasized that use of the log-normal fitting procedure to extract data is necessary largely because of the inadequacies of the reporting. If data were reported in narrower ranges and with explanations of the treatment of notional doses and of measurements less than the limit of detection, then the use of the log-normal technique to extract information would

be unnecessary. It would be preferable if the original data were analysed more completely to give the collective dose and average dose, based on either the number of workers issued with dosimeters or the number of workers receiving measurable doses. It would also be desirable to report the distribution of doses, especially high individual doses, and the fractions of the collective dose delivered at individual doses above and below an annual dose level such as 15 mGy.

C. LIFETIME DOSE PREDICTIONS

34. In Annex E of the 1977 report [U3] the Committee used a simple linear extrapolation to predict lifetime doses for a few categories of workers for whom data on the average dose and years of employment were available for individuals. Very few new data have become available on which even this simple treatment could be used [B22, I4], and it is clear that the treatment does not take adequate account of the complexities of the prediction.

35. It was hoped that the simple treatment would have stimulated more investigation of the relationship between the rate of accumulation of dose over the years of a person's employment and the total dose received in that employment. This investigation would need to consider whether higher doses are received randomly throughout a group of workers or consistently by the same individuals each year, whether workers tend to stay in the high dose occupations for long periods or move into lower dose occupations with age, or even whether the reverse happens. It would also be useful to investigate the correlation between predictions based on historical records using various assumptions and actual total doses.

36. Clearly such investigations, which by their very nature deal with actual doses to individuals, can only be performed by those authorities having access to individual dose records. The Committee would like to encourage those authorities to carry out such investigations and analyses and report the results in a suitably anonymous fashion so that the privacy of the records of the individual workers is safeguarded.

III. THE NUCLEAR FUEL CYCLE

37. The nuclear fuel cycle is a major identified practice giving rise to occupational exposure. It was discussed in some detail in the 1972 [U2] and 1977 [U3] reports of the Committee and is generally well documented. There are considerable quantities of data on occupational dose distributions available. All aspects of the complete fuel cycle, whether or not carried out globally, are considered, except for the final treatment and disposal of the major wastes including high level wastes.

38. The output from the nuclear power industry is the quantity of electric energy supplied. Whether the reported energy is that generated by the station or that supplied for use, i.e., less that consumed by the station, is sometimes uncertain. The uncertainty is small compared with other uncertainties in the data but in general the energy supplied for use has been used in this Annex. Of more importance is whether the installed generating capacity may be a more appropriate measure in some circumstances for normalizing than energy generated. This is particularly the case with the reactor component of the fuel cycle, as a reactor may be shut down for most of a given year so that the collective dose per unit energy generated becomes very large and may even be infinite if the shut-down is for a complete year. For this reason the collective dose per unit energy generated is not a very meaningful quantity to calculate for individual reactors on an annual basis, and figures should be averaged over several years if possible. The appropriate averages can give indications of performance over a complete power programme or over several years. For the other stages in the fuel cycle, averaging over a complete power programme is necessary in any case so this difficulty does not arise.

A. URANIUM MINING AND MILLING

39. The main source of irradiation of uranium miners is exposure to radon and daughters. This subject is discussed in detail in Annex D in which data for several countries are reported; a summary of recent data is given in Table 2 for the late 1970s. For the United States the average exposure of about 5000 miners is reported by Richardson [R1] as approximately 4 WLM per year. This is considerably higher than the average reported in Annex E of the 1977 report [U3] of 1.4–1.9 WLM per year and that reported by Cook and Nelson [C9] of 1.1 WLM per year. The exposures reported by other countries are in agreement with the lower values reported for the United States, with Canada having about 4000 underground workers exposed to approximately 0.75 WLM per year on average and workers in France exposed to approximately 1.5 WLM per year on average. Taking all these values into account, an appropriate annual average exposure to radon daughters can be taken as about 1.5 WLM which can be converted using the appropriate coefficient from Annex D (8.4 mSv/WLM) to an annual effective dose equivalent of about 13 mSv. Underground miners are also exposed to some gamma radiation. This was estimated in the 1977 report as 10 mGy per year as a world-wide average. More recent Canadian data show a value closer to 1–2 mGy, but these are based on very few measurements and are believed to be low [A1].

40. Surface uranium miners have a very much lower exposure to radon daughters (see Annex D) and their dose from external radiation is also lower at about 1–2 mGy per year [A1, M1, L13]. It seems reasonable therefore to take the estimate of annual effective dose equivalent from external and internal irradiation of surface uranium miners as about 5 mSv.

41. Overall the collective dose per unit energy generated can be obtained but it is a somewhat complex calculation depending on the production of ore, taken as 3 t a^{-1} of natural uranium per miner, and the efficiency of conversion. The best available estimate of the latter is likely to be that made during the International Nuclear Fuel Cycle Evaluation [I11] which is that for current reactors the natural uranium requirement is about 200 t $[GW(e)\ a]^{-1}$. The estimate in Annex E of the 1977 report was 0.05 man rad $[MW(e)\ a]^{-1}$ (0.5 man Gy $[GW(e)\ a]^{-1}$) from gamma radiation plus 0.1 man rad $[MW(e)\ a]^{-1}$ (1.0 man Gy $[GW(e)\ a]^{-1}$) of alpha irradiation of the lungs. A similar calculation carried out for mines in Argentina gave a higher value for 1977–1979

of about 20 man Sv [GW(e) a]$^{-1}$ but this dropped to 4 man Sv [GW(e) a]$^{-1}$ in 1980 [P20] associated with a shift from underground to surface mining. Taking the INFCE value of 200 t [GW(e) a]$^{-1}$ of natural uranium, the mining rate of 3 t a^{-1} and the average effective dose equivalent of 13 mSv a^{-1}, then the collective dose equivalent per unit energy generated is 0.9 man Sv [GW(e) a]$^{-1}$. An appropriate rounded estimate of the collective effective dose equivalent per unit energy generated is 1 man Sv [GW(e) a]$^{-1}$.

42. The most detailed surveys of doses received by workers at uranium mills are for the United States in 1975 [C1, C9] and 1978 [B17]. An extrapolated total of about 1000 workers was estimated to be involved at an average measurable annual dose equivalent of 4 mSv in 1975, but only 2 mSv in 1978. The MR was estimated for the 1975 data as 0.2. A similar survey for millers in Australia [S19] gave average weekly doses of 0.06 mSv to 73 workers for a six-month working period in 1979–1980. The collective dose equivalent of 2 man Sv, taking the more recent estimate, and based on an energy production of 32 GW(e) a in the United States in 1978, makes a minimal contribution to the collective dose equivalent per unit energy generated of less than 0.1 man Sv [GW(e) a]$^{-1}$ and is not included as a separate item in the summary.

B. FUEL MANUFACTURE

43. New information on doses received at fuel manufacturing plants is available from Canada and India. In addition, there are data from the United Kingdom and the United States to update those given in Annex E of the 1977 report. Some new information on the doses to workers concerned with fuel manufacture under licence to the United States Nuclear Regulatory Commission have been published. These data are summarized in Table 3 [C1, U4, B1, B17]. Log-probability plots of the data from 1974 to 1978 are given by Brooks et al. [B17] and show a steady reduction in both $\overline{D}$ and MR. Only workers with measurable doses have been included. The results for 1975 are taken from a special survey [C1]. In 1977 [B1] and 1978 [B17] more detail was given of the activities within the category of fuel processing and fabrication which includes uranium and plutonium fuel fabrication and scrap recovery, reprocessing plants, and the manufacture of plutonium sources. The collective dose for plants engaged in uranium fuel fabrication in 1977 and 1978 were 10 and 9 man Gy, respectively, which in each case is about 60% of the total. Even this value will overestimate the dose from fuel fabrication because other activities are also carried out at some of these plants. The energy generated in the United States during the four-year period 1975–1978 was 100 GW(e) a [B22, H4]. Assuming that about 60% of the dose received in fuel processing and fabrication results from the fabrication of fuel for power reactors, the collective dose per unit energy generated from fuel manufacture was 0.5 man Gy [GW(e) a]$^{-1}$. This estimate is considerably below that given in Annex E of the 1977 report [U3] because of the decreased doses and increased energy generated; this may reflect an approach to equilibrium since in the early 1970s fuel was being fabricated for the large number of reactors which were shortly to become operational.

44. The doses to fuel fabrication and fuel enrichment workers in the United Kingdom from 1976 to 1978 [U5,

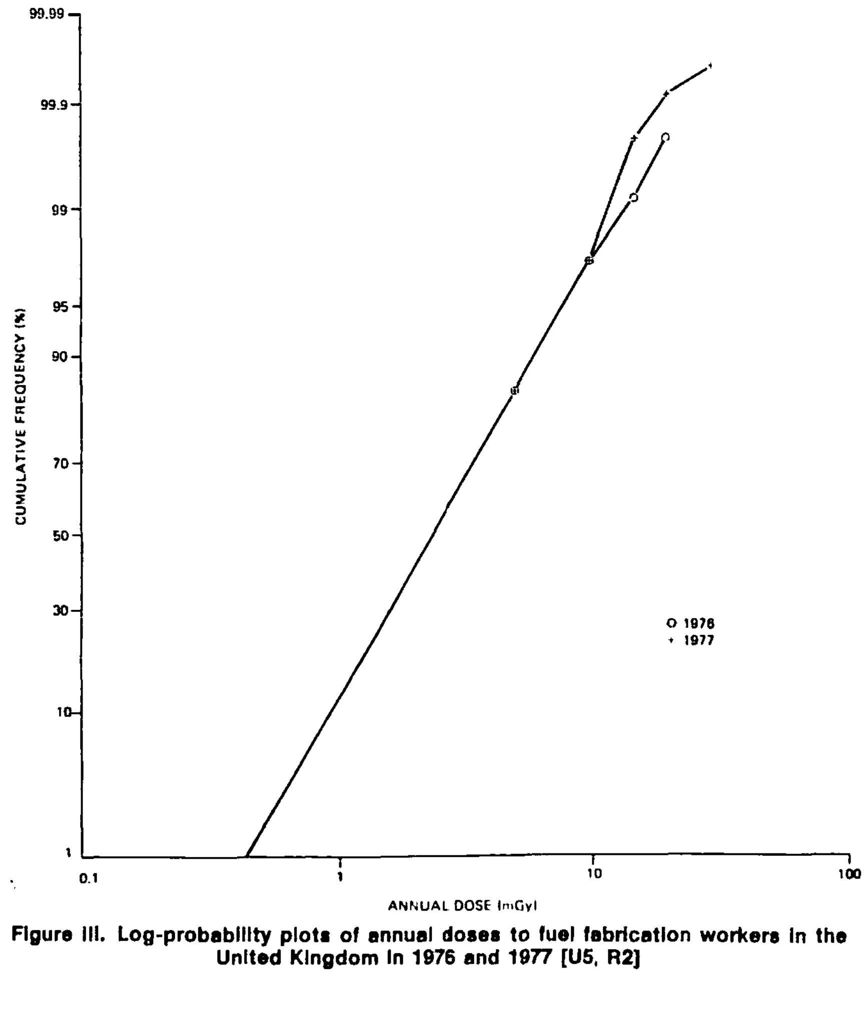

Figure III. Log-probability plots of annual doses to fuel fabrication workers in the United Kingdom in 1976 and 1977 [U5, R2]

R2, U16] are summarized in Table 4. Log-probability plots for fuel fabrication workers are shown in Figure III. The electrical energy generated in the United Kingdom during each of these years was about 3.3 GW(e) a [G2, N1] so the collective dose per unit energy generated has dropped from about 2.0 to 1.5 man Gy $[GW(e)\ a]^{-1}$. This may still be an overestimate since some fuel would have been manufactured over this period for the new advanced gas-cooled reactors (AGRs).

45. Data have been published on the doses received by workers at the six fuel manufacturing plants in Canada [A1]. The annual collective dose and annual average doses from 1970–1978 are shown in Table 5. One company refines uranium and produces UO_2 and UF_6 while the other five fabricate fuel. The doses have decreased since 1974 although production has increased. The collective dose per unit energy generated has dropped from about 1 man Gy $[GW(e)\ a]^{-1}$ in the mid-1970s to about 0.25 man Gy $[GW(e)\ a]^{-1}$ in 1978 since several large stations started to produce power in 1977 and 1978.

46. The doses received by workers in fuel fabrication facilities in India from 1966 to 1978 have been published [I4]. Of about 800 workers at the factory, 300 to 400 received measurable doses in recent years, with an annual average dose in 1978 of 1 mGy and a collective dose of 0.4 man Gy. The electrical energy generated in India up to the year 1978 was 2.4 GW(e) a which, combined with the total collective dose over the period of 6.6 man Gy, leads to a collective dose per unit energy generated of about 3 man Gy $[GW(e)\ a]^{-1}$.

47. Annual average doses from fuel fabrication are generally low, being about 0.3 mGy in Argentina [P20], 1 mGy in Canada and 2–3 mGy in the United Kingdom and the United States from 1977–1978. The fraction of the collective dose delivered above 15 mGy is in general small, often approaching zero.

48. The more recent estimates of dose per unit energy generated from fuel manufacture are considerably reduced from the previous estimates, possibly because the fuel manufacturing industry is reaching equilibrium with the number of reactors in use. There is some difficulty in estimating the collective dose per unit energy generated since fuel manufacture may take place some time before the fuel is used to generate energy. Results from the United Kingdom show that the collective dose equivalent per unit energy generated has remained fairly constant from 1972 to 1977 at 1.5 man Sv $[GW(e)\ a]^{-1}$, whereas in the United States the figure has dropped from 2.5 in 1973–1974 to 0.5 in 1975–1978. The best estimate at present for Canada is 0.25 man Sv $[GW(e)\ a]^{-1}$; an estimate over many years for India yields 3 and for Argentina 0.2 man Sv $[GW(e)\ a]^{-1}$ [P20]. Overall probably the best estimate of the collective dose equivalent per unit energy generated from fuel manufacture is 1 man Sv $[GW(e)\ a]^{-1}$.

C. REACTORS

49. More data on occupational exposure to radiation are reported for reactor operation than for any other area. The major focus in this Annex is to assess trends in the collective dose, individual average doses, the number of workers per unit energy generated for different reactor types, and to see whether these correlate with the age of the plant, experience in operation, reactor type, etc. Another objective is to revise the overall estimate of collective dose equivalent per unit energy generated. The difficulties, referred to earlier, of normalizing to the energy generated are clearest in this section. Especially for water reactors, most doses result from routine or special maintenance, so in the year during which such maintenance occurs, when there is less energy generated because of shut down, collective doses are high. Thus the only figures of use are those derived over several years for many reactors. Normalized results are not useful indicators for a particular plant in any one year. It is assumed throughout that all the dose accumulated by workers on reactors is related to the energy produced so that doses due to training or other jobs are included. In many countries, transient workers are brought in for short periods during the year to carry out special maintenance; it is not always clear whether these have been included but where possible this is specified.

1. Light water reactors

50. Most light water reactors are installed in the United States, where considerable operating experience has now been accumulated. Summaries of occupational radiation exposure at light water reactors in the United States up to 1979 have been published by the United States Nuclear Regulatory Commission [J1, P1, B18, B22]. Some of the data presented in Annex E of the 1977 report [U3] have been revised to make them consistent with those which are now required to be reported to the United States Nuclear Regulatory Commission.

51. The data reported on boiling water reactors (BWRs) and pressurized water reactors (PWRs) for the years 1973–1979 are summarized in Tables 6 and 7. Over this period the number of reactors included increased from 12 to 25 BWRs and from 12 to 42 PWRs. The most striking trend is the increase in the number of workers per reactor with measurable doses, especially over recent years, and the corresponding decrease in the average individual dose; by contrast, the annual average collective dose has remained reasonably steady. Figure IV shows the trend in the annual average values of the number of workers and collective dose per reactor, together with the average dose per worker for all LWRs in the United States from 1971 to 1979 [B22]. The average value for the collective dose per unit energy generated over the 5 years 1975–1979 is 12 man Gy $[GW(e)\ a]^{-1}$. The figures for individual reactors in any one year are very much more variable, ranging from less than 1 to over 100 man Gy $[GW(e)\ a]^{-1}$ for PWRs in 1979; this shows again that only broad average values of this parameter are useful. A detailed analysis was carried out [B22] of the data from each reactor over the 5-year period 1975–1979. This showed that in general the newer plants had lower collective doses per reactor, annual average doses to workers and collective doses per unit energy generated than older plants. It was noted that some of the increases in collective doses in 1979 resulted directly from safety-related actions required by the United States Nuclear Regulatory Commission following the Three Mile Island accident.

52. Figure V is a log-probability plot of the annual doses to workers at all LWRs in the United States in 1978 [B18]. This distribution, which is typical of recent years, shows clearly the effect of efforts to reduce the number of individuals exposed to high annual doses.

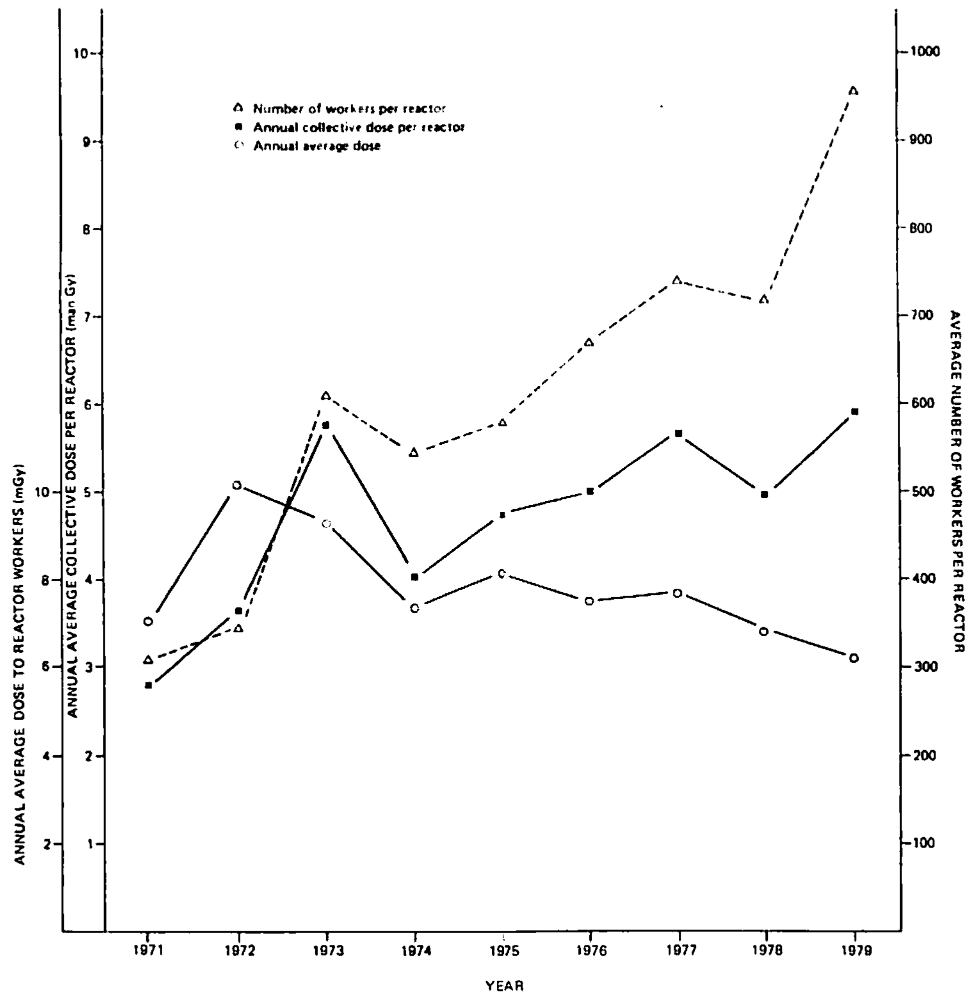

Figure IV. The number of workers and annual collective dose per reactor, and the annual average dose for all LWRs in the United States 1971–1979 [B22]

The value of MR for the distribution is 0.55, representing a steady decrease from a figure of 0.73 in 1973 [B22].

53. There are also a considerable number of light water reactors in Europe, (excluding the United Kingdom), in Japan and in some other countries. Data from these are not in all cases reported systematically but some collated information is published by the IAEA [I5, I6, I7] and a survey has been carried out by the Nuclear Energy Agency of OECD [I8]. Additional and more detailed reports have been published for the Federal Republic of Germany [M3, P4] the German Democratic Republic [S1], Japan [M15], Spain [F1, G4], Sweden [P2] and Switzerland [K2, G3, P3]. Table 8 gives details for some of the BWR reactors by country and installed capacity; it also gives, for some recent years, the average value of the collective dose per unit energy generated. Table 9 gives the same data for PWRs. It is noticeable that the values of average collective doses per unit energy generated are quite variable, due to the relatively small numbers of reactors in some cases. In most cases high values occur when reactors were shut down for a significant part of the year. For some countries only the collective dose from all LWRs is available; in the Federal Republic of Germany in 1978 this was 41 man Gy giving a collective dose per unit energy generated in that year of 4 man Gy $[GW(e)\ a]^{-1}$ and a cumulative average up to 1978 of 17 man Gy $[GW(e)\ a]^{-1}$ [M3]. The trend in collective dose per unit energy generated has been examined by the Nuclear Energy Agency [I8] as a function of the age and type of reactor. There is some evidence for an increase with time in service for BWRs commissioned prior to 1973 but this is less marked for those commissioned later; there is a slight but similar trend for PWRs. This increase is attributed to build-up in the reactor circuits of gamma-emitting activation products such as ^{60}Co, leading to increased doses during maintenance.

54. A clearer trend which emerges from the Nuclear Energy Agency survey [I8], and from special studies in the United States [B22] and the Federal Republic of Germany [M3], is towards lower collective doses per unit energy generated. In general, taking into account all those countries reporting data but giving due weight to the United States experience, the best estimate of the average collective dose equivalent per unit energy generated from LWRs is 10 man Sv $[GW(e)\ a]^{-1}$. This is the same as the estimate in Annex E of the 1977 report [U3].

55. The average dose to reactor workers is reported in the references cited for many of the countries referred to earlier and does not appear to have changed very greatly from the estimate made in Annex E of the 1977 report. In general, annual average doses to reactor workers range from 3 to 8 mGy. However, there has been a significant increase in the number of workers per reactor, particularly in the United States, for which data are available, in the period from 1970 to 1980. In the United States the number of workers per reactor has

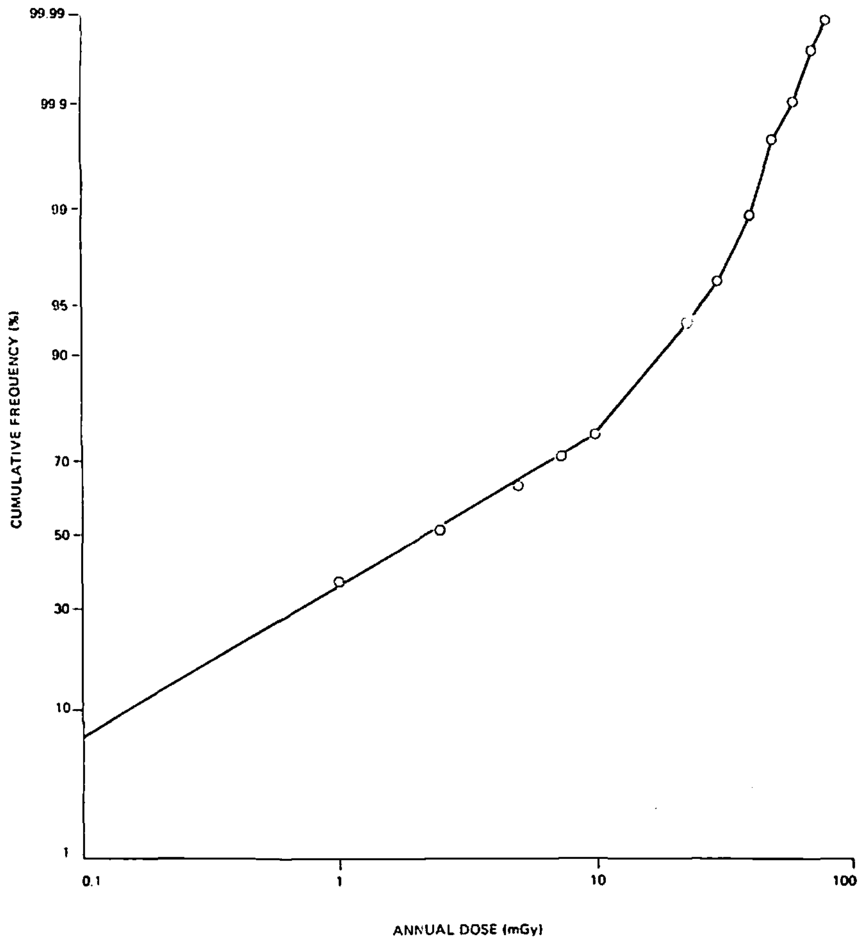

Figure V. Log-probability plot of annual doses to workers receiving measurable doses at LWRs in the United States, 1978 [B18]

increased by a factor of between 3 and 4 over this period.

56. Only in a few of the special studies are sufficient data available on the dose distribution to enable the value of the collective dose distribution ratio MR to be assessed. The values for both direct employees and contractors at Swedish LWRs are all less than 0.3 over the years 1976–1978 [P2]; that for Swiss LWRs fell from 0.6 in 1976 [P3] and 1977 [K2, G3] to 0.4 in 1978 [G3] and was accompanied by a drop in the annual average dose; for the small and rather old BWR at Gundremmingen in the Federal Republic of Germany the collective dose distribution ratio has remained close to 0.7 from 1970 to 1977 [P4]. As already mentioned, the collective dose distribution ratio for United States LWRs has fallen from about 0.7 to a value approaching 0.5 [B18].

2. Heavy water reactors

57. New information has been published concerning the Canadian CANDU reactors [A1]. The stations were not named in the paper but they can be identified from the information given by using reference [N1]. The average doses for the stations operating in 1977 were given and these are shown with the characteristic of the stations in Table 10. The collective dose equivalent per unit energy generated by all stations between 1972 and 1978 is given in Table 11. In 1975 and 1976 the collective doses at Pickering were higher than in other years because the pressure tubes in two of the four units were changed [L1]. In most years about 30% of the dose at Pickering results from the intake of tritium [E3]. The collective dose per unit energy generated from 1972 to 1978 inclusive is 7 man Gy $[GW(e)\ a]^{-1}$, slightly lower than the value in Annex E of the 1977 report [U3].

58. The annual average doses shown in Table 10 vary considerably between the five stations. Until 1977 the situation was characterized by the practice at Pickering, then the largest station, and an annual average dose approaching 10 mGy was reasonably representative [A1]. The dose distribution at this station in 1976 is shown in Figure VI. In 1977 Bruce A became operational and initial experience is that both external and internal annual average doses are very much lower, being less than 1 mGy combined. It is not yet clear if this early experience has been maintained. As can be seen from Figure VI, the value of the collective dose distribution ratio MR for Pickering in 1976 was difficult to estimate due to the extreme deviation at higher doses; it is probably about 0.3. No value has yet been established for Bruce but it will clearly be very low for 1977.

59. Some information has been published for the 335 MW(e) net installed capacity pressurized heavy water reactor at Atucha, Argentina [P20]. The annual collective and average doses are summarized for the period 1977–1979 in Table 12. The values of collective dose and average dose include a contribution of about 20% from internal exposure due to tritium. The collective dose per unit energy generated is also shown in Table 12: as is to be expected for a single reactor, it is quite variable.

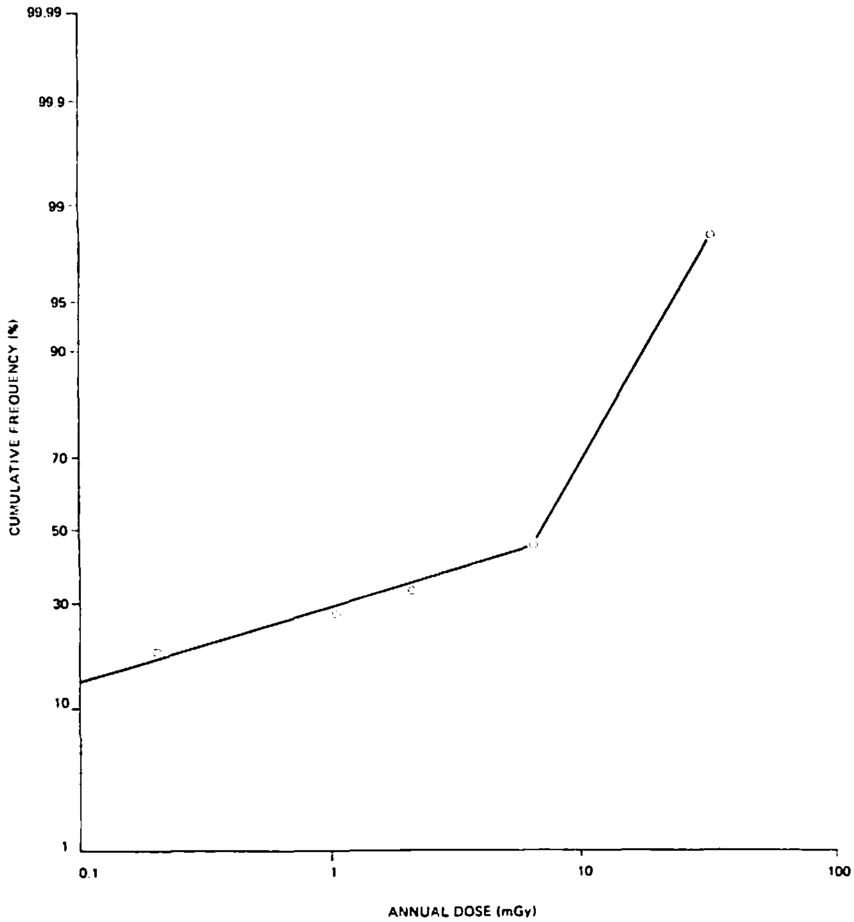

Figure VI. Log-probability plot of annual doses to workers at Pickering heavy water power station in Canada, 1976 [A1, N1]

60. Giving due weight to the Canadian experience with CANDU, for which the collective dose per unit energy generated is about 7 man Gy [GW(e) a]$^{-1}$, and taking note of Atucha in Argentina which is also a heavy water reactor, the collective dose equivalent per unit energy generated from heavy water reactors does not seem very different from that at light water reactors at about 10 man Sv [GW(e) a]$^{-1}$.

3. Gas cooled reactors

61. Most experience with gas cooled reactors is in the United Kingdom where they have been installed and operating for many years. There have been no significant changes in the pattern of dose distribution, the number of workers or the average dose since the 1977 report [U3]. The doses received by workers at all the United Kingdom GCRs in 1975, 1976 and 1977, and the Central Electricity Generating Board stations only in 1978 and 1979, are summarized in Table 13 [G5, H18, G7, G6, U5, P5]. The value of MR is less than 0.15 for all the years reported. In 1977 the South of Scotland Electricity Board station at Hunterston employed over 1000 more contractor employees than usual; many of these may only have been employed for short periods. Most of the reactors are of the Magnox type; two advanced GCRs started operation in 1976. The collective dose per unit energy generated is also given in Table 13 [U3, G2, H2, H4]; this has decreased slightly during the 1970s; the figure for the years 1972–1979 inclusive is 6 man Gy [GW(e) a]$^{-1}$. Those data which are available on GCRs installed in France, Italy, Japan and Spain [I5, I6, I7] are in broad agreement with the United Kingdom experience.

4. Fast reactors

62. There are no commercial fast reactors yet operating but some indications of doses can be obtained from data on the prototype fast breeder reactors (FBRs) in the United Kingdom and France. At the French LMFBR, Phenix, in 1975–1976 a total of nearly 300 workers were exposed with a mean dose of about 0.1 mGy [M4]. Since the maximum individual dose was 2.7 mGy, the collective dose distribution ratio MR was zero. The energy generated was only 0.1 GW(e) a [I6] but this gave a value of 0.3 man Gy [GW(e) a]$^{-1}$ for the collective dose per unit energy generated. Further data on the collective doses over recent years is given in Table 14 [P9]. Data for the prototype FBR at Dounreay, United Kingdom, are given in Table 15 [A2]. The maximum individual dose received in 1977 was below 4 mGy and therefore in that year the collective dose distribution ratio MR was zero; data on dose distributions for the previous years were not given.

63. It appears from these preliminary data that prototype FBRs, at least, can be operated with low annual average doses and give low values for the collective dose per unit energy generated. Very few workers are exposed to annual doses above 15 mGy, but it is not clear whether these dose distributions include routine or special maintenance.

5. Nuclear powered ships

64. The radiation exposure of personnel on the Nuclear Ship "Otto Hahn" over the period 1969 to 1977

has been reported [R4]. The annual average dose rose after the first two years but then remained fairly constant between 3 and 6 mGy. The distribution of doses to the 50 crew members in 1974, which was a year of normal operation, was given in detail; the collective dose distribution ratio was zero and the collective dose was 0.2 man Gy. Higher doses are received by some individuals during maintenance periods; the collective dose to personnel during a maintenance period of unspecified duration was calculated as 0.2 man Gy with a collective dose distribution ratio of 0.2. The doses received by the crew of the Nuclear Ship "Mutsu" are also very low; no crew member exceeded a dose of 0.1 mGy during the test cruise in 1974 [I10].

65. In addition to these demonstration nuclear powered merchant ships, several navies operate nuclear powered ships of various types. Information on doses to workers at United States naval nuclear propulsion plants and their support facilities [M10] over the years 1970 to 1978 is summarized in Tables 16 and 17. As would be expected, the doses, collective doses and MR values are very much higher at the shipyards where maintenance is carried out than on ships, tenders or at submarine bases.

6. Doses to particular occupational subgroups

66. There is a general problem in comparing doses received by different occupational subgroups in that breakdowns of workers into occupational categories or job descriptions in different countries do not exactly match; however, workers can be divided into a few broad groups. Workers have been assigned to one of four broad areas: operations, maintenance, health physics and supervision/ administration. Where the job description did not match exactly the most appropriate category was selected. Sometimes workers are brought in for specific maintenance jobs; it is not always clear whether their doses are included in the reported data, but where possible this is indicated.

67. The collective doses received at BWRs and PWRs in the United States from 1977 to 1979 are shown in Table 18 for the four broad areas given above [P1, B18, B22]. The category given in the references as "engineering" was assumed to be principally a supervisory function. Just over half of the total collective dose in each year is received by contract workers. Special and routine maintenance account for about 70% of the collective dose received at United States LWRs.

68. Similar information for LWRs in a number of other countries, generally for 1978, is shown in Table 19. The distribution is expressed as the percentage of the total collective dose quoted in each category. Where the average annual doses were given or could be calculated, the highest values were about 10 mGy. Average doses of this general level were received by some health physics workers [P2] and by particular groups of maintenance workers such as insulation installers or mechanics [P2, S2]. Another category of work giving rise to a high proportion of the collective dose is inspection. This has been recently identified at United States reactors [B22] and has been cited as important at reactors in the Federal Republic of Germany [U6]. Inspection requirements can be part of routine operating procedures or quality assurance programmes, or they can be specially devised by regulatory bodies in response to fault analysis; the situation will differ from country to country.

69. With regard to LWRs, data from the United States and other areas summarized above clearly show that the majority of the collective dose is received during maintenance operations. These are separated in water reactors from the normal operation of the reactor since they are generally performed during identified shutdown periods. However, it must be recognized that planned maintenance is essential to the operation of a reactor, and therefore both categories of work should really be considered part of normal operations. A more difficult category is "special maintenance" which is not very clearly defined but presumably means maintenance jobs either not foreseen, though proving to be routine, or jobs of an infrequent nature. In recent years about half the collective dose received by workers in the United States reactors was due to special maintenance.

70. The annual average dose to different groups of workers at Canadian nuclear power stations in 1979 is given in Table 20 [A10]. In general the most exposed groups, as they have been for some years [A1, J2], are mechanical maintenance workers, control technicians and operators. About 30% of the collective dose is received by operators and a similar proportion by mechanical maintenance workers. A similar study for workers on the Atucha reactor [P20] showed about 60% of the collective dose being received by maintenance workers, 25% by operators and 15% by health physics workers.

71. Information on the doses received by different occupational groups has been published for two United Kingdom Magnox reactors; a summary of this is given in Table 21 [K3, K4]. No one group stands out as receiving much higher annual average doses than others, although maintenance workers tend to be among the most highly exposed, as do health physicists at Dungeness. However, the highest annual average dose was 3.4 mGy to instrument maintenance workers [K3].

72. Many detailed studies have been carried out on particular operations at individual reactors. These studies can often reveal areas of work giving rise to high individual doses or high collective doses [G9, P4, S3, H4, V1, P2, U6, H4, R3, M5, M6, M7, A3, I8]. These are then clear areas for study to see whether doses can be further reduced to levels which are as low as reasonably achievable. This is however a matter for local study and is not appropriate for consideration in detail by the Committee.

73. The general conclusion is that there are two major sources of collective dose at all reactors. These are the routine operations and maintenance which are essential to the operation of the reactor, have presumably been planned for in the design, and which cannot be much affected in broad terms once the reactor has been designed and built. The other source is unforeseen, special maintenance, which has often to be carried out in areas without designed routine access, under high dose rates and in cramped or otherwise poor working conditions. It is a feature of concern that this source of exposure appears to be dominating the collective dose per unit energy generated from water reactors; however much of this work is unscheduled repairs to essential components, which clearly has to be carried out.

D. FUEL REPROCESSING

74. Although fuel reprocessing is not universally practised at present, some form of extraction of unburnt fissile material from the used fuel elements and some form of processing for eventual disposal of the elements is very likely to form part of the complete fuel cycle. It is accordingly useful to examine the experience in fuel reprocessing, while recognizing that this is limited to a small number of countries and that the plant design and historical operating conditions may well not represent the best current potential for new plants. Reprocessing, incorporating waste treatment, is identified in Annex E of the 1977 report as one of the largest contributors to the collective dose per unit energy generated. That estimate was based only on the Windscale plant in the United Kingdom. Data are now also available on the plant at Cap de la Hague in France.

75. The distribution of doses in 1977 at the Magnox fuel reprocessing plant, the plutonium fuel fabrication plant and other plants operated by British Nuclear Fuels Ltd. (BNFL) at Windscale, United Kingdom, is plotted in Figure VII. This clearly shows the effect of efforts to restrain annual doses within a limit of 50 mGy.

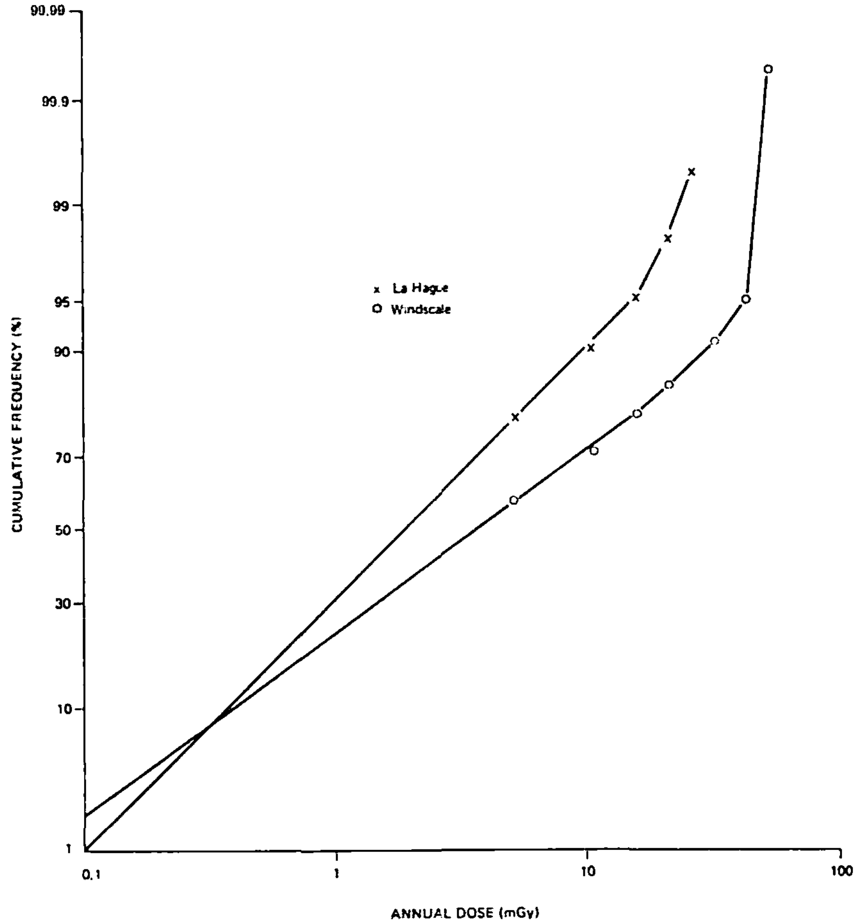

Figure VII. Log-probability plot of annual doses to fuel reprocessing workers at Windscale, United Kingdom, in 1977 and at Cap de La Hague, France, in 1978 [J3, U16]

The parameters for 1976 to 1978 are summarized in Table 22 [U5, U16, R2]. The throughput of the plant in terms of energy generated has been estimated from the ^{85}Kr discharges [C2, H5, H6, H7, A4] using the normalized value of 14 PBq $[GW(e)\ a]^{-1}$ from Annex F. The collective dose per unit energy generated is given in Table 23. The average value over the 8-year period is 18 man Gy $[GW(e)\ a]^{-1}$. These values are overestimates for reprocessing alone because of the other activities on the site. It is very likely that any new plant built to reprocess fuel will have a significantly lower collective dose per unit energy generated [P6].

76. Information on the doses received by workers at the COGEMA reprocessing plant at Cap de La Hague, France, for the period 1970–1979 has been made available [B4, J3]. Until 1976 only fuel from gas cooled reactors was reprocessed at La Hague; the first reprocessing of LWR fuel took place during 1976 [C2]. The occupational doses are summarized in Table 24 from 1970 to 1979 [J3, J9]. The log-probability plot of doses for 1978 is shown in Figure VII. The throughput of the plant in terms of energy generated has been estimated from the ^{85}Kr discharges between 1972 and 1976 [C2]. The collective dose per unit energy generated for this period is given in Table 25; the average value over the 5 years of 6 man Gy $[GW(e)\ a]^{-1}$ is less than half that estimated for Windscale.

77. The dose distribution at both plants indicates substantial work forces exposed to significant doses. The annual average dose at Windscale has been constant or has dropped slightly over recent years; however, this decrease in average dose has been accompanied by an increase in the number of workers and a roughly constant collective dose. This may be correlated with efforts to reduce all individual doses to less than 50 mGy per year. Data for Cap de la Hague over the 1970s show the annual average dose at about half that received by Windscale workers but decreasing

slightly in recent years, also accompanied by an increase in the number of workers and a relatively constant annual collective dose.

78. There are some data for different work groups at Cap de la Hague given in Table 26 [B4] and there are also data taken at the Karlsruhe plant [S5], but the differences in average dose are not great and it is hard to separate out different groups within the overall operation of what is essentially a chemical plant. A similar comment applies to the doses reported by the Idaho Chemical Processing Plant [C5] and the Savannah River Reprocessing Plant [H9].

79. Some information is available on the demonstration fuel reprocessing plant at Mol, Belgium, and is shown in Table 27 [O1]; the plant however stopped reprocessing in 1964. The average doses were comparable with those at Windscale in the United Kingdom, as was the MR value, both being higher during the years for which reprocessing took place. Some data, which are given in Table 28 [S5], are also available on the pilot fuel reprocessing plant at Karlsruhe; workers at this plant had average doses similar to those at Cap de la Hague.

80. Normalizing to the fuel throughput is difficult since other work takes place at Windscale and it is not at all clear that doses from the operation of the plant bear any close relationship to the throughput. Nonetheless, assuming that all the doses at Windscale are related to fuel reprocessing gives a collective dose per unit energy generated of about 18 man Gy [GW(e) a]$^{-1}$ and for Cap de La Hague a similar assumption gives about 6 man Gy [GW(e) a]$^{-1}$. It is worth noting that the projected collective dose per unit energy generated from new fuel reprocessing plant is much lower. It may well be that a realistic estimate of the likely global collective dose equivalent per unit energy generated from fuel reprocessing and waste processing for disposal is about 10 man Sv [GW(e) a]$^{-1}$. This would imply that the overall impact of this part of the fuel cycle will eventually be comparable with that from reactor operations.

E. RESEARCH AND DEVELOPMENT

81. In Annex E of the 1977 report the Committee estimated that the largest single contributor to the collective dose per unit energy generated was research and development. It was noted that this was reasonable in the early stages of a nuclear power programme but that the proportion should decrease as the number of operating power reactors increased. It is also relevant that countries such as the United States, on which the estimate was largely based, carry out major research backup both for domestic and overseas reactors. A further important factor is that many of the research organizations carry out research and development not connected with the nuclear fuel cycle but the doses are often reported in a collected fashion.

82. Research associated with the nuclear industry in the United States has been carried out mainly by the Energy Research and Development Administration (ERDA), which was taken over by the Department of Energy (DOE) in 1977. ERDA also covers accelerators, irradiation facilities and work for defence purposes, such as nuclear weapons manufacture and naval reactors. The information for 1975–1979 is taken from ERDA and DOE annual reports [U8, U9, U17, U18, U19]. The summary includes reactor work, fuel fabrication and processing, uranium enrichment, general and other research; a considerable proportion of work under these categories may include defence work. The doses to workers with measurable exposure are summarized in Table 29. The total collective doses at the ERDA and DOE sites allocated by the Committee to nuclear research and development is about 75%. The electrical energy generated during the period 1975–1979 was 128 GW(e) a [B22] which would lead to a collective dose per unit energy generated of about 3 man Gy [GW(e) a]$^{-1}$.

83. Information has been received on the doses to workers at the Atomic Energy of Canada Limited sites [M8] where nuclear research is carried out for the Canadian power programme and for production of isotopes for medical use. The average and collective doses from external exposure and tritium intake are given in Table 30 for 1970–1978. Over 4000 workers were monitored each year. The distribution of doses from external radiation and tritium combined for workers receiving measurable exposure in 1978 is plotted in Figure VIII; the MR value was estimated as about 0.4 in 1978. The electrical energy generated in Canada during the period 1972–1978 was 13.6 GW(e) a [A1]. The collective dose per unit energy generated for this period was about 6 man Gy [GW(e) a]$^{-1}$.

84. In the United Kingdom most nuclear research is undertaken by the United Kingdom Atomic Energy Authority (UKAEA). In addition the Central Electricity Generating Board (CEGB) runs a research laboratory at Berkeley. The doses for the period 1975–1979 are summarized in Table 31 [T1, G7, H18, G6]; the collective dose distribution ratio MR is in general less than 0.3. Figure VIII gives a log-probability plot of the doses at UKAEA establishments for 1977. The electricity supplied during the period 1975–1977 was 9.3 GW(e) a [G2] which leads to a value for the collective dose per unit energy generated of 13 man Gy [GW(e) a]$^{-1}$. The UKAEA also undertakes research work which is not associated with the nuclear power programme, so that this value is likely to be an overestimate.

85. One of the major nuclear research centres in the Federal Republic of Germany is at Karlsruhe. The annual collective and average doses to all workers and the average doses received by certain groups of workers are given in Tables 32 and 33 [K5]. Since there is in the Federal Republic of Germany another nuclear research centre at Jülich, for which no estimates of dose are available, a value for the normalized collective dose equivalent cannot be calculated.

86. Some information is shown in Table 34 on doses to nuclear research and development workers at the Institute for Reactor Research in Switzerland [K2, G3, P3], the Atomic Energy Industry, excluding nuclear power production, in Japan [M15], at Mol in Belgium [D1] and in Argentina [G8, P20]. Using the values for the energy generated in each country over the period shown [I6, I7, H2, S4], and assuming all the research was in support of the power programme (except where specified) the collective doses per unit energy generated were calculated and are shown in Table 34. These may be overestimates in some cases other than for Argentina where, for example, over half of the dose at the sites covered is received in connection with non-nuclear power research.

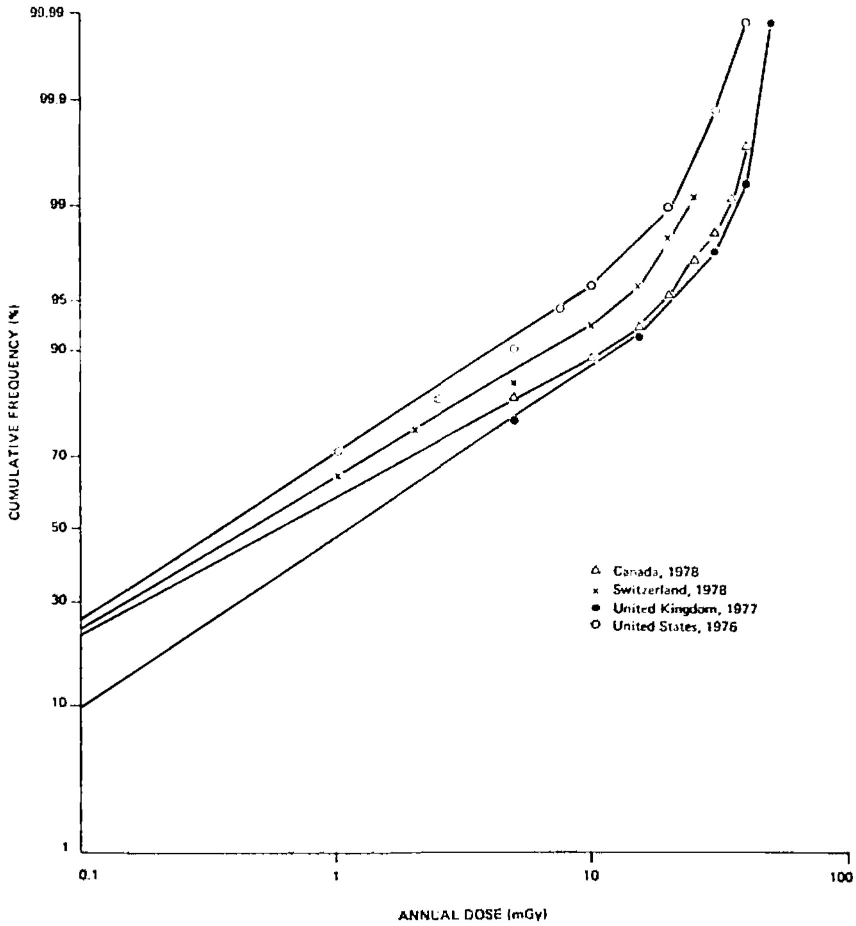

Figure VIII. Log-probability plot of annual doses to workers in nuclear power research and development in various countries [G3, M8, U9, U16]

87. In conclusion, data have been presented on doses and dose distributions in research and development for several countries; there are considerable differences if these are normalized to the energy produced by the country. A further complication is the existence of other non-nuclear power related research which may be carried out within establishments. For example, if this had been included in the data for the United States in Table 28, then the overall figure for the collective dose per unit energy generated would have been 4 man Gy $[GW(e)\ a]^{-1}$. Nonetheless, if the figures are taken at face value and the collective doses from the major nuclear oriented research establishments are related to the energy generated in each country, as has been done in this section, the values of collective dose per unit energy generated range from 1 man Gy $[GW(e)\ a]^{-1}$ in Japan and Switzerland to 13 man Gy $[GW(e)\ a]^{-1}$ in the United Kingdom. The high values obtained for the United Kingdom and some other countries should not be allowed to dominate this picture, since much of this research is thought to be related to development of future reactor types or to non-nuclear power research. Giving due weight to the value for the United States, which clearly also supports reactors in many other countries, a global estimate of about 5 man Sv $[GW(e)\ a]^{-1}$ seems more reasonable than the value of 14 man Gy $[GW(e)\ a]^{-1}$ given in Annex E of the 1977 report.

F. SUMMARY

88. The summary of the contributions to the collective dose equivalent per unit power generated is given in Table 35. The largest contributors are reactors and fuel reprocessing plants; the value for nuclear research is much lower than that estimated in Annex E of the 1977 report [U3]. The estimates in that report were based largely on experience in the United States and the United Kingdom, but data from a number of other countries are now available. It should be noted that this collective dose is received at essentially the same time as the energy is produced and may not be directly comparable with collective dose commitments calculated in other Annexes. There is reasonable consistency, between values from various countries, of the collective dose per unit energy generated for reactors, but there is wider variation in other parts of the fuel cycle. The values given above are regarded as representative of world experience, although they are biased towards the United States because of its comparatively large nuclear power programme. Based on an estimate of 70 GW(e) a as the total energy generated in the world in 1979 [I12], the annual occupational collective dose equivalent due to the nuclear generation of electric energy in that year can be assessed as about 2000 man Sv. This may also be expressed for comparison purposes as about 0.5 man Sv per 10^6 population.

IV. MEDICAL USES OF RADIATION

89. Medical uses of radiation may be separated into two broad categories, diagnostic and therapeutic. These differ in that for diagnostic radiology or nuclear medicine the objective is to use the minimum exposure to radiation of both subject and medical workers to obtain the desired information; for therapy, however,

the intent is to deliver a well defined but generally very high dose to the appropriate tissues of the patient and at the same time the minimum dose to the medical workers. It is not always easy or even possible to separate these categories in the reported data. The Committee wishes to encourage the identification and reporting of the type of work leading to doses to medical workers. By the nature of medical work, exposures are frequently non-uniform over the body so the effective dose equivalent may not be easily obtainable from the dose indicated by a dosimeter, due to the energy or spatial inhomogeneity of the radiation field [M14]. More data on these aspects would be of use.

A. DIAGNOSIS

1. Diagnostic radiology using external beams of radiation

90. This is the most widespread and common use of radiation in medicine. It has been surveyed in many countries from the point of view of doses to patients but there are not such well identified data on occupational doses. The situation is further complicated because workers within this general field may have different jobs; doses are often reported separated between medically qualified or other professional workers and technicians [M9] or between all workers in general practice and in hospitals [C1, P9]. However, by appropriate grouping it is possible to obtain an indication of the annual average doses to all workers in this area, which range from fractions of a mGy to a few mGy. Collective doses are also obtainable, as are estimates of the numbers of workers. For certain procedures the doses to radiologists may be highly non-uniform. Under these circumstances information on doses to particular body organs or tissues will be of use. The data available have not been reviewed but, for example, information on the doses to hands, chest and head of surgeons carrying out angiography has been reported by several authors [B23, K13, L12].

91. Doses to medical workers under license from the United States Nuclear Regulatory Commission have been reported in 1975 in a special survey [C1]. The distributions of doses for different categories are plotted in Figure IX. Only a small proportion of the

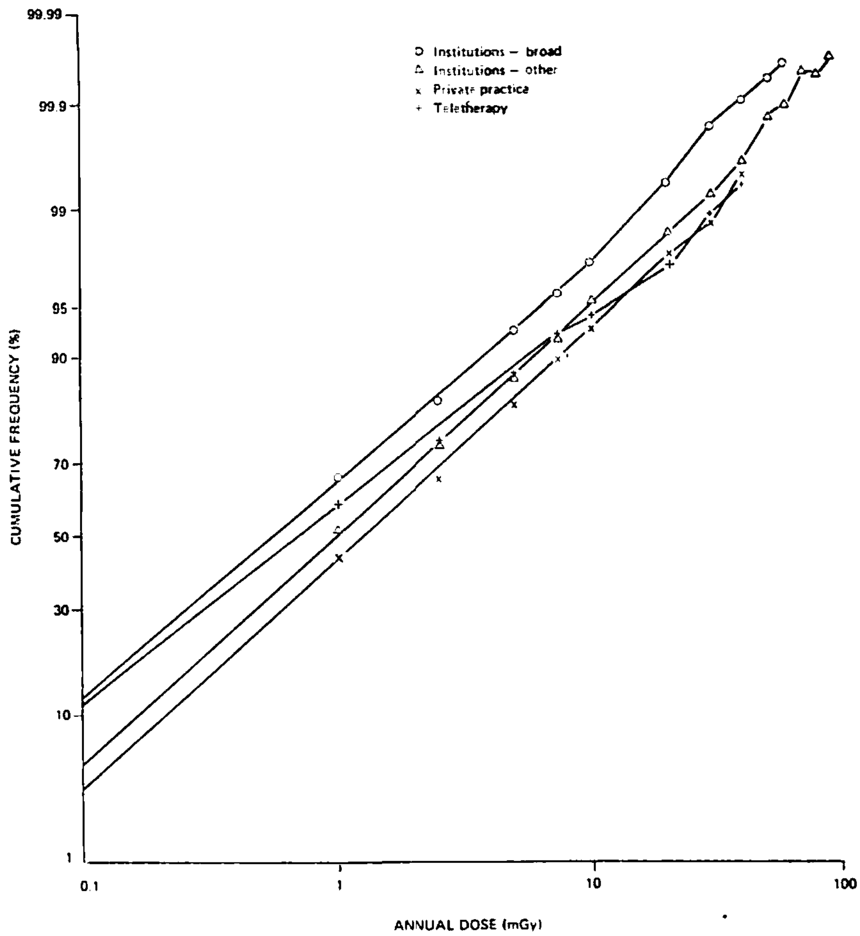

Figure IX. Log-probability plot of doses to medical workers with measurable exposure in the United States in 1975 [C1]

licensees took part in the survey. A more comprehensive review is available for 1978 [B17] and a summary of the data from this is given in Table 36. Data are also available for the workers who are monitored by the Bureau of Radiological Health [M9] and are summarized in Table 37 for 1972–1978. The values of MR are all less than 0.1. The average doses to different groups connected with radiology are given in Table 38; they are generally low but radiologists are consistently the most highly exposed group.

92. The doses received by Swiss medical workers for 1976–1978 are summarized in Table 39 [P3,' P7, P8]. Information on the doses received by medical workers

using diagnostic x rays in France, monitored by the Service Central de Protection Contre les Rayonnements Ionisants, is given in Table 40 [P9, S17].

93. For many countries it is not possible to tell from the reported results which medical workers are connected with diagnostic radiology, other forms of diagnosis or with therapy; frequently all medical workers are considered as a single category. On the basis that for any given country most medical workers will be connected with diagnostic radiology rather than any other specialty, these results are reported in this section and may be found in Table 41 together with more detailed results from some other countries. The results for Australia [S19] and Canada [A10] are based on recent detailed surveys; the results for Australia have been extrapolated from a survey estimated to cover 50% of workers, as have those for Japan [M15]. The Japanese data are for all workers with x rays and will therefore include dental workers. The figures given for the Federal Republic of Germany are extrapolated from those reported by eight states [F2]; they are expected to be supplemented in due course through an extensive statistical exercise being carried out by Färber et al. [F6, F7]. No further data are available from the United Kingdom on the doses received by medical workers; however, the number of medical workers has been re-estimated as 33 000 [T1]. On this basis the collective dose to medical workers, most of whom are connected with diagnostic radiology, would be 70 man Gy, assuming the same annual average dose equivalent of 2.1 mGy as in Annex E of the 1977 report.

94. Estimates of throughput in terms of numbers of films used for x-ray examinations are available and therefore some comparison of the collective dose per unit throughput can be made and are given in Table 42. Data given in Annex E of the 1977 report [U3], those given earlier in this section and some other sources [T1, E1] have been used to compile Table 42. The data do not necessarily correspond to the same year but only data relating to years after 1970 have been used. Information on the number of x-ray diagnostic examinations alone are used, since most examinations are of this type and they are probably adequate as an indicator of total practice. It is not clear how useful such comparisons are in this field, since the number of films used may not directly relate to benefit to patients if there are other reasons for taking x rays. However, the average values are fairly constant at about 1–2 man Sv per 10^6 films. This figure varies from about 0.5 to 4 man Sv per 10^6 films.

95. Dentists form a large sub-category of practitioners who use x rays for diagnosis. Exposures of this group are characterized by large numbers of workers being exposed to low individual doses, as shown in Table 43 for several countries. The annual average doses range from almost zero to 0.5 mGy.

96. A smaller group also using x rays for particular purposes are chiropractors and osteopaths. These groups use x rays to aid in subsequent non-radiation treatments and the use is closer to diagnosis than therapy. Doses to this group are not in general separately identified, although information from Australia indicates about 100 workers exposed to annual average doses of 0.2–0.3 mGy [S19] and from Canada several hundred workers at annual average doses less than 0.1 mGy [A10]; more data would be of interest.

2. Diagnosis with incorporated radionuclides

97. Diagnosis with incorporated radionuclides, normally referred to as nuclear medicine, is characterized by the use of particular radionuclides which may be chosen because they concentrate in specific organs. The problems of dose control are in most cases more related to protection against ingestion or inhalation, especially during preparation, analysis and administration of radiopharmaceuticals. However, there is also an external radiation field from some nuclides such as ^{99m}Tc, which can give very high dose equivalent rates to the hands, approaching some hundreds of mSv without syringe protection [G12]. The use of nuclear medicine has increased rapidly in many countries over the last decade, and it would be helpful to have more detailed data on exposures of organs or tissues from particular radionuclides, together with estimates of quantities used, numbers of workers exposed, etc. Data are given in Table 44, showing annual average whole-body doses which are fairly low, of the order of 1–2 mGy, although extremity doses could be much greater. The collective dose distribution ratio is close to zero in all cases. Data on doses to nursing staff from the residual activity in patients on return to wards would also be useful in assessing the overall impact of nuclear medicine on occupational exposure.

B. RADIOTHERAPY

1. Radiotherapy with external beams

98. Radiotherapy with external beams is carried out inside well shielded rooms and, since there is no residual radioactivity in the patient, there is no resulting dose to nursing staff when the patient is returned to the ward. Doses to medically qualified staff are therefore very low, as the operation of these facilities is generally the responsibility of other technically or professionally qualified staff. These staff are not always easily identifiable in dose records but assuming that they are within the category reported in the United States as working with teletherapy, or in France as workers with cobalt or conventional radiotherapy as given in Table 45, then annual average doses would appear to be about 2–3 mGy. The collective dose distribution ratio MR, where this can be obtained from the data given, is in the range 0.2 to 0.4.

99. There are some special categories of treatment under this general heading of radiotherapy. One such is identified in data from France as high energy treatment, with other than conventional x-ray or cobalt-60 therapy machines. There is no reason why such treatment should give rise to higher doses to the operators than conventional machines and indeed the data for France shown in Table 45 confirm this. Another special category is the use of neutron beams, for which some data have been reported [S6]. As would be expected from a correctly designed and shielded facility, no staff exposures to neutrons were recorded. However, activation of the target led to annual average doses from external radiation of the order of a few mGy to medical, nursing and other professional staff.

2. Radiotherapy using interstitial and intracavitary sources

100. To obtain highly localized doses to malignant tissues in certain positions in the body it is necessary to

apply or implant sealed sources of various types. This has traditionally been carried out manually by skilled medical workers, including surgeons and gynaecologists, who could receive substantial doses especially to their hands and faces, which could not be effectively shielded. Subsequent to implant, the nursing staff could also receive substantial doses while ministering to the patients on the wards.

101. The trend in these treatments has been towards finding ways to reduce both sources of occupational exposure. This has been carried out primarily by trying to develop techniques such as afterloading, which enables the surgical or other preparatory procedures to be carried out without the source, which is introduced mechanically afterwards. This also makes possible the use of more active sources than could be directly handled, reducing irradiation time, and usually enables the source to be removed before the patient is returned to the ward. More information on these procedures, and the changes in occupational doses resulting from their introduction, would be useful. For example, a survey of four hospitals in Boston, United States [C3] over the period 1973–1976 showed annual average doses to nursing staff between 0.2 to 1.5 mGy; afterloading procedures were used in most cases. In Australia annual average doses to nurses of patients with sealed sources were 4.4 mGy to over 200 nurses in 1974 and 1978 [S19].

102. Because of the highly non-uniform irradiation possible, it is difficult to be clear about the relevance of reported annual average whole-body doses such as the few mGy reported for French workers in interstitial and intracavitary therapy [P9].

3. Radiotherapy with unsealed sources

103. Treatment of malignancies in some organs can be carried out using radiopharmaceuticals which preferentially seek the organ in question. The most common examples are treatment of hypothyroidism and cancer of the thyroid with radioiodine. This form of treatment raises special problems of nursing and aftercare, as the activity is gradually lost from the patient by the normal bodily elimination processes, including exhalation and perspiration as well as excretion in urine and faeces. There may also be a substantial external dose rate, depending on the radionuclide used.

C. SUMMARY

104. A number of recommendations have been made of areas where more data could be gathered and reported to clarify the situation regarding occupational doses in medical practice. One general recommendation is that there should be a clearer indication of the type of work leading to the dose and of the uniformity or otherwise of the exposure of body organs or tissues. More information on the exposure of certain groups of workers is required; these are nuclear medicine workers including nurses, radiotherapy workers especially those changing to afterloading techniques, chiropractors and osteopaths.

105. Doses to workers involved in the use of radiation for medical purposes are highly variable, and in some instances are characterized by an extremely non-uniform distribution over the body. It is also not possible to identify and quantify the beneficial output of all medical work, although an attempt has been made in paragraph 94 to relate the doses from diagnostic radiology to the number of films processed. To obtain an indication of the total occupational exposure it is probably best to express this as the annual collective dose equivalent per million population of the country, on the grounds that total medical care should be roughly proportional to population. Even from the few available data, however, it is clear that this measure varies greatly from one country to another. Some estimates are given in Table 46. A representative value to adopt for the annual collective dose equivalent per million population in countries with a high standard of medical care seems to be 1 man Sv per 10^6 population, although a considerably lower figure would be more appropriate for countries with a lower usage of radiation in medicine.

V. USES OF RADIATION IN INDUSTRY AND RESEARCH

106. Radiation is now used for very many purposes in general industry. Most of these uses involve sealed radioactive sources giving rise to such trivial doses that the users are not normally regarded as radiation workers. Examples include such ubiquitous products as smoke and fire detectors and thickness gauges. Of more interest to the Committee are those occupations in which the users are exposed to radiation doses comparable with those received from other uses of radiation. Those research and development uses of radiation which it is possible to identify separately from the research in support of the nuclear power programme are also covered in this section.

A. INDUSTRIAL RADIOGRAPHY

107. Industrial radiography may be divided into two categories of use, those in which the radiography installation is reasonably permanent and samples are tested under moderately controlled conditions, and those in which sources are used under fairly primitive conditions on construction or other sites. The standards of control, supervision and protection are markedly different in the two cases. This is illustrated later by the preponderance of over-exposures of workers in the latter category, site radiographers.

108. When dose information is reported, these categories of use are frequently not separated. Data from the United States for NRC licensees shown in Table 47 [B2] identify radiographers as receiving annual average doses of 2–3 mGy, but this is the result of averaging over more than 10 000 workers and may well obscure some imbalance in the dose distribution for certain smaller subgroups. This was investigated by Brooks et al. [B17] who examined the differences between radiography at single or multiple locations. The annual average doses to those working at multiple locations were higher than to those at single locations but still only 5 mGy for those with measurable exposures. The collective dose distribution ratio MR was 0.4, similar to the values in Table 47. The annual average doses received by non-NRC licensed workers engaged in radiography were lower, generally less than 2 mGy. Similarly annual average doses to industrial radiographers as a group were reported in France [P9], Canada [A10] and Japan [M15] as about 1–2 mGy. There is some apparent discrepancy between the annual average doses and dose distributions as reported and

the widely held view that industrial radiographers are among the most highly exposed groups of workers. This view is supported to some extent by the fact that workers in this group are more liable to receive accidental over-exposures than those in any other occupation. This is an area which was identified by the Committee in its previous report as being unclear and further information specifically on the exposure of site radiographers would be extremely useful.

B. LUMINIZING

109. Radioactive materials have been used in luminizing for decades but there has recently been a trend away from the use of radium to tritium and, to a lesser extent, to ^{147}Pm. The practice of luminizing is still fairly widespread. Tritium is used both mixed with a phosphor in a paint and as a gas enclosed in a phosphor-lined glass walled tube. Data on the internal doses to luminizers are available for several countries and are shown in Table 48, although this group cannot be separated in the United States data.

110. Annual average doses are fairly high, ranging up to 15 mGy, and are due almost entirely to internal doses from tritium, with a dose distribution showing a substantial proportion of workers receiving annual doses above 15 mGy, although only a few are exposed above 50 mGy. This is illustrated, for several groups of workers, by the log-probability plots in Figure X.

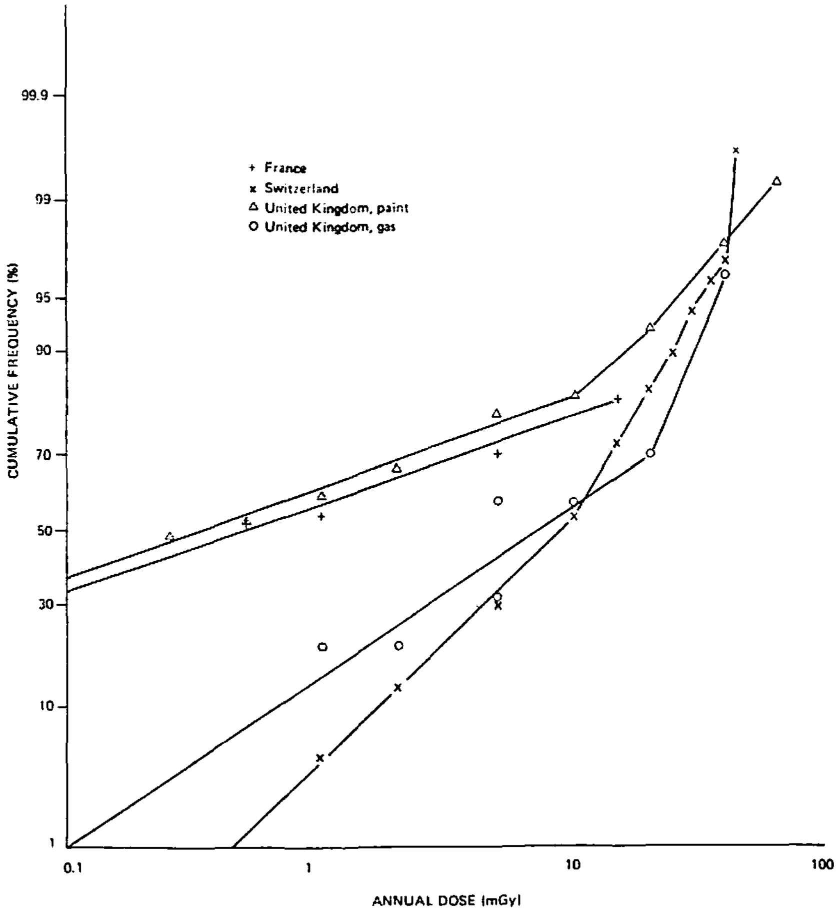

Figure X. Log-probability plot of annual doses to luminizers in the United Kingdom in 1976, in Switzerland in 1978, and in France in 1978 [P8, P9, T1]

C. RADIOISOTOPE PRODUCTION

111. Reporting conventions for this type of work vary from country to country. Most of the industrial preparation of sealed and unsealed sources in the United States is described under the category of by-product material, although this also appears to include some production of radiopharmaceuticals. A similar situation applies in the United Kingdom where The Radiochemical Centre Ltd. (now known as Amersham International Ltd.) produces both medical and industrial sources using the same workforce. This is one area in which workers are potentially exposed to intakes of radionuclides into the body. It is somewhat surprising that there is not more reporting of internal doses; even if checks were to show that intakes and doses were very low this would still be useful information. The annual average doses reported in the United States were a few mGy for a workforce of 2000–3000 people, including primary distributors [B17]. The radiochemical industry in the United Kingdom operates at annual average doses of 7–8 mGy for a workforce of nearly 1000 [T1]. Production workers are not separately identified in other countries.

112. Some workers at airports and other places are irradiated during the transport of these packages of sources. A major study in the United States has estimated the annual average dose to cargo handlers, who might be expected to have the highest doses of these groups, as less than 1 mGy, with a maximum dose to any individual of less than 5 mGy [S7]. Annual average doses to pilots and other aircrew from radioactive packages, most of which would be expected

to contain radiopharmaceuticals, have been assessed as less than 0.01 mGy [B6]. The maximum individual dose to any individual flight attendant from radioactive packages has been estimated as 1 mGy [T2].

D. OTHER INDUSTRIAL USES

113. There are many other uses of both sealed and unsealed sources ranging from tracer experiments to well logging and other measurement systems. Information on exposure from these is not separately identified in many countries; that which is available is shown in Table 49. It appears that there may be many thousands of workers associated with such uses, and some occupations such as well logging, in which the annual average dose equivalent is estimated to be as high as 5 mSv, could merit further investigations, such as those carried out by Romanova [R6] and summarized in Table 49.

114. All these industrial uses of radiation give rise to radioactive wastes, often of large volumes and not suitable for homogeneous treatment or packaging. Disposal of such wastes is handled in most countries somewhat separately to disposal of wastes from the nuclear power industry. However, the doses to this group of workers are difficult to identify from the reported data. In the United States the annual average dose to a group of less than 100 workers in this category was estimated in 1975 as 13 mGy [C1]. This small group showed one of the highest average doses of any identified occupational group. A lower annual average dose of 6 mGy was however reported for waste disposal workers in 1978 [B17]. More data and evaluation of the situation in other countries would be useful.

E. RESEARCH

115. Many workers in a vast range of disciplines use radiation as a research tool. As has been pointed out in Section III E, many large research establishments serve the nuclear power industry but also carry out other research on the application of radionuclides or radiation. This is frequently difficult to separate and may have been included in that section. In the majority of these research disciplines the annual average doses are very low, of the order of 1 mGy, as is shown by the comprehensive United States survey summarized in Table 50 [B17, U17, U18]. Some research categories, however, give higher average doses: these are workers with accelerators who receive annual average doses of 4–5 mGy and investigators using unsealed sources who, although there are only 20 of them, receive annual average doses of 10 mGy.

116. Doses to research workers in other countries for which data are available are given in Table 51. Annual average doses are very low, generally less than 1 mGy, with very few doses above 15 mGy.

F. SUMMARY

117. There are many industrial uses of radiation under the control of many different employers and often under different regulations in different countries. The reporting of data is not therefore consistent, and the Committee has identified many special occupational groups on which more reported information would be highly desirable. These groups are site radiographers, radioisotope producers (especially those receiving internal doses), general dental workers, workers in radioactive waste disposal, research workers with accelerators and those handling unsealed sources. It may be that some of these groups are receiving the highest annual average doses of any occupationally exposed workers.

118. Data are reported in several countries on all industrially exposed workers, with only a limited breakdown into different work categories, or none at all. The numbers of workers are quite large in some cases. There is no clearly identified common measure of output from industry or research so, as for medical workers, the collective dose equivalent per million population is used as a measure of the total occupational exposure. Some estimates are given in Table 52. A reasonable average estimate of the annual collective dose equivalent per million population for industrialized countries is 0.5 man Sv per 10^6 population; a considerably lower figure would be more appropriate for countries that are not heavily industrialized.

VI. OTHER EXPOSURES TO RADIATION

119. Most of the occupations referred to in this chapter are those in which, by virtue of the materials or surroundings, some increased exposure to radiation is incurred by workers. This radiation is generally of natural origin. Workers in these occupations are generally not subjected to individual monitoring although the doses may be estimated from area monitoring or special checks.

A. CIVIL AVIATION

120. The major source of exposure of air crew is the increase of cosmic radiation with altitude; the small additional doses due to transport of radioactive packages have been discussed in paragraph 112. The dose to any individual thus results from a combination of flying time and altitude, modified to some extent by the latitude, etc. The average additional annual dose from cosmic radiation has been assessed as 1–2 mGy [B6, T1, B7]. Approximately 70 000 air crew are exposed at about this level in the United States and a further 20 000 in the United Kingdom. The doses received by security personnel working near baggage inspection systems have also been surveyed [S8]; annual average doses were less than 1 mGy.

B. NON-URANIUM MINING

121. Data were given in Annex E of the 1977 report of exposure of non-uranium miners to radon and radon daughters; the subject is reviewed in detail in Annex D. New data from a number of countries show that average exposures are variable but can exceed 4 WLM per year depending markedly on the local conditions. Average exposures in mines for metals such as iron, zinc, lead and copper appear to be about 1 WLM for work forces of typically a few thousand workers. There are some indications that exposures in large coal mines are somewhat lower.

C. OTHER WORK UNDERGROUND

122. Other occupations which entail exposures to radon and radon daughters include work in under-

ground spaces such as telephone communication tunnels and water conduits. Some hydroelectric power stations also have considerable underground workings. A small amount of information is available and is presented in Annex D, which shows that although only a few workers are involved, annual average doses can be similar to those in non-uranium mines.

123. Radon spas have for many years been places to which people resort for supposedly beneficial treatments. These treatments include exposures to radon-rich atmospheres and waters. In this report, workers in such spas have not been classified as medical workers exposed to radiation, since there is no known medical benefit of the treatment. The small amount of data summarized in Annex D shows that radon daughter exposures of some of these workers, though admittedly only of small numbers, approach or even exceed those of uranium miners, and may reach 40 WLM per year.

D. USE OF PHOSPHATE FERTILIZERS

124. Although the levels of activity concentration of natural radionuclides in phosphate fertilizers are not great, the quantities of material involved and the processes used indicate a potential for irradiation of the workers. This has been intensively studied in the Federal Republic of Germany [P10]; the survey showed that annual average doses were generally less than 0.2 mGy and the maximum annual dose to any individual was less than 0.5 mGy. The annual collective dose was estimated to be about 2 man Gy.

E. SUMMARY

125. Very large numbers of people are exposed to higher than average levels of natural radiation in the course of their work, but generally to quite low levels of occupational dose. Only in a few cases need this exposure be the subject of control or even of interest. The most important practical case is that of radon daughter exposure to underground workers, especially non-uranium miners and radon spa workers. The largest collective dose is from civil aviation. On the basis of the small amount of data reported, the annual collective dose equivalent per million population appears to be of the order of 1 man Sv per 10^6 population.

VII. ACCIDENTAL EXPOSURE TO RADIATION

126. In this chapter the Committee reviews information on accidental exposures to radiation. This subject was not discussed in Annex E of the 1977 report [U3] and was covered only briefly in the 1972 report [U2]. The objective of this review is to identify those types of accident that occur most frequently and which give rise to clinical consequences. Minor accidents and simple over-exposures are not included but are referenced in some instances. There is no obvious dividing line between an inadvertent over-exposure to radiation as a result of bad practice and an accident leading to over-exposure. This is particularly clear where industrial radiography sources have been involved and over-exposures have occurred as a result of insufficient training or poorly maintained equipment. The information on accidents is categorized by the sectors of the industry in which the work leading to the accident was carried out.

127. Information on major accidents is usually given in the published literature. Minor accidents are reported regularly to some national regulatory bodies and often these reports are freely available. Only the data made available to the Committee or found in the published literature could be included and therefore the coverage may be incomplete. The Nuclear Regulatory Commission in the United States publishes regular reports on occupational exposure, including over-exposures, and also reports to Congress on abnormal occurrences for its licensees. The Bureau of Radiological Health in the United States keeps records of accidents where clinical effects have occurred. The Health and Safety Executive in the United Kingdom makes similar reports to Ministers on accidents covering nuclear installations. Details of accidents are included in the Annual Reports of the Ministry of the Interior in the Federal Republic of Germany. Other sources of useful data are the reports of the cytogenetic dosimetry services in France and the United Kingdom. Many of their investigations are initiated because an abnormally high dose has been recorded on a dosimeter; this may or may not be a genuine high dose to a person. The more recent data presented in this chapter have been taken mainly from the sources described above. The emerging picture is by no means complete but may probably be taken as fairly representative of accidents occurring throughout the world.

128. Data available to the Committee on accidents that have occurred in the nuclear industry since 1945 and which had clinical consequences are given in Table 53. The majority of these occurred in the early development of nuclear power and were criticality excursions, several at experimental reactors. Some of those early accidents resulted in deaths after whole-body doses estimated to exceed a few Gy, although in certain cases heroic measures such as bone marrow transplants may have helped to avert death. No similarly serious accidents have been reported since the mid 1960s; indeed only one accident since then resulted in clinical symptoms. A number of accidents in the 1970s have involved minor wounds, usually when the worker was using a glove box [S12, O2, U10, O3, L3, H13]; in many of these the radioactive material was removed by excision. Another type of accident involved inhalation of various radionuclides, usually inside process buildings as a result of faults in the air flow pattern [F4, S13, H11, U10, B10, L2, E2]; in some cases a chelating agent was administered in an attempt to accelerate elimination of the radionuclide [S13]. Other accidents generally involved unsuspected high dose rates [U10, P14, U4, U11] or contamination [P13, B11, L4, H14] but no remedial actions were needed.

129. Accidents in general industry (excluding industrial radiography) since 1960 which had clinical consequences are given in Table 54. Only one death was reported after a whole-body dose of 10 Gy but in several instances isolation was required and in others amputations had to be carried out. Most of those accidents occurred either during servicing or use of large irradiators or generators capable of delivering high dose rates; many of them were clearly the result of inadequate carrying out of safety precautions by the workers involved, although some were due to equipment failures. Other reported accidents which did not result in clinical consequences were generally of the same type [H15, P15, P17, C8, G11, P18, B13, Y1, L4,

P7, L9, J4, D3]. Apart from the systematic reporting in the Federal Republic of Germany of minor accidents involving internal contamination [B25, B26], two other minor accidents have been reported involving exposure to tritium gas as a result of leaks or cracks in vessels or connecting lines [L6, L9].

130. Accidents involving industrial radiographers since 1960 which had clinical consequences are shown separately in Table 55. Some other serious accidents but not involving workers, some of which resulted in deaths, occurred when high activity sources were kept in homes for long periods by people who did not know what they were [K6, M12, Y2, S17]. Some of the other serious clinical consequences resulted from what appears to have been intentional exposure on the part of those involved.

131. A further 53 minor accidents involving over-exposures to radiation have been reported in the period 1969–1979, mainly from the United Kingdom and the United States, which have systematized reporting of such incidents [P13, D5, P15, P17, U10, B15, J5, P18, L4, U13, U4, U14, L9, B1, D6, H17, U15].

132. Almost all the accidents occurring in the normal course of work are attributable either to deliberate flouting of safety precautions or to equipment failures resulting in sources being left exposed. It appears that the first type, and many of the second type, have as their root cause lack of appreciation for the hazard, possibly through over-familiarity or insufficient training and explanation. Use of simple dose rate monitors would have shown the hazard in the majority of cases.

133. The relatively small number of accidents in research and development outside the nuclear power industry since 1960 which had clinical consequences are shown in Table 56. Several of these resulted from deliberate circumventing of safety measures by scientists who clearly should have been aware of the hazards; others were due to equipment failure. A few additional similar accidents have been reported [U10, P18, P7, L9, L1, L10, W3].

134. No accidents involving medical workers, and which led to clinical consequences, have been reported in the last decade. Of the accidents reported, the majority were a result of faults with switches or interlocks controlling x-ray generators [P15, J6, P14, P19, L4, L9]. One accident of internal contamination with ^{131}I was also reported [B11].

SUMMARY

135. Considering the number of workers involved with radiation and radioactivity over the last several decades, the number of deaths and serious injuries is not large. Many of these occurred in the early development phase of nuclear reactors when safety precautions were very much less stringent. Nonetheless there is one area of work, industrial radiography, in which the mishandling of sources and equipment failures has lead to a large number of reported accidents with potentially serious consequences.

VIII. CONCLUSIONS

136. The Committee reviewed occupational exposure in detail in Annex E of the 1977 report and suggested methods for the analysis of dose distributions and criteria against which to assess the parameters extracted from the dose distributions. These methods of analysis have been used by several organizations since the report was published; in this Annex they have been refined slightly. It still appears that the observation that data often fit a log-normal distribution, especially at lower doses, enables an improved estimate of the parameters of a distribution to be made. The techniques for extracting the relevant parameters are described in this Annex.

137. The three characteristics of the dose distribution previously identified by the Committee as of interest may still be used to describe distributions in a useful fashion. These characteristics are:

(a) The annual average dose, which is related to the average level of individual risk;
(b) The annual collective dose, which is related to the total impact of the practice;
(c) The ratio of the annual collective dose delivered at individual doses exceeding 15 mGy per year to the total annual collective dose, which is related to the proportion of workers exposed to higher levels of individual risk.

138. The reference distribution introduced in the 1977 report has not proved as useful as was hoped and the Committee has therefore decided to revert to the basic parameters given above which may be extracted from any dose distribution, rather than normalizing them to the reference distribution.

139. In previous reports the Committee has adopted the convention that all numerical results reported by monitoring services represent the average absorbed dose in the whole body while recognizing that it is almost always the reading from the dosimeter which is reported, without consideration of the relationship between this and the absorbed dose in the body. This is, however, still regarded as a reasonable convention in that most data are on external exposure of the whole body to ionizing radiation. The same convention has again been adopted in this Annex. In situations where exposure of the body may be non-uniform, especially in medical practice, it may be misleading to average across different types of work as the relationship between reported dosimeter reading and average absorbed dose in the whole body will not be constant.

140. In Annex E of the 1977 report the Committee used a very simple linear extrapolation to predict lifetime doses for a few categories of workers for whom data were available. The Committee had hoped that this simple treatment would have stimulated more investigation of the relationship between the pattern of accumulation of dose over the years of a person's employment and the total dose received in that employment. Clearly such investigations can only be carried out by those authorities having access to individual dose records. The Committee would like to encourage such investigations and analyses, the results of which should be reported in a suitably anonymous fashion.

141. A major re-evaluation of the doses occurring in the nuclear fuel cycle has been carried out. Revised estimates of the collective dose equivalent per unit energy generated have been obtained for each part of the cycle and are shown in Table 35. The most notable features are that the estimated doses from reactor operations are unchanged from the previous report but

that the estimated doses from reprocessing and research, which were much less soundly based, have now been considerably reduced. Based on an estimate of 70 GW(e) a as the total nuclear energy generated in the world in 1979, the annual occupational collective dose equivalent associated with it can be assessed as about 2000 man Sv. This may also be expressed as about 0.5 man Sv per 10^6 population for comparison purposes.

142. Reported exposures of uranium miners to radon and daughters are reviewed in Annex D. Although some data from the United States show an average exposure of about 4 WLM per year, other reports from the United States and those from other countries are closer to 1 WLM per year. Taking all these into account, an appropriate annual average exposure to radon and daughters appears to be about 1.5 WLM, which can be converted to an annual effective dose equivalent of about 13 mSv.

143. Annual average doses to workers on power reactors have been maintained at about 5 mGy; however this has been attained by a significant increase in the number of workers per reactor, particularly in the United States for which most data are available, in the period from 1970–1979. In general the number of exposed workers per reactor in the United States has increased by a factor of between 3 and 4 over this period for light water reactors. Annual average doses at heavy water reactors are in general similar to those at light water reactors and those at gas cooled reactors have remained low at about 2–3 mGy.

144. The general conclusion is that there are two major sources of collective dose at all reactors. One of these is the routine operations and maintenance which are essential to the operation of the reactor, have presumably been planned for in the design, and cannot be much affected in broad terms once the reactor has been designed and built. The other source is unforeseen special maintenance, which must often be carried out in areas without designed routine access, in high dose rates and in poor working conditions. Much of this work consists of unscheduled repairs to essential components, which clearly has to be carried out. This source of exposure currently appears to be dominating the collective dose per unit energy generated from water reactors.

145. More data are now available on doses to commercial reprocessing plant workers in France as well as the United Kingdom, together with some information on research or pilot plants. The results indicate substantial workforces exposed to dose distributions with an annual average dose of about 10 mGy. It is emphasized, however, that many of these are historical data, often based on old plants, and may well not be typical of the more recent plants or of doses to be expected in the future.

146. Data have been presented on doses and dose distribution in research and development work connected with the nuclear power industry in several countries. Annual average doses generally range from 1–5 mGy, but large numbers of workers are involved.

147. Exposures during medical uses of radiation have been briefly reviewed but there is not much recent information. Medical uses have been divided into two major categories, diagnosis and therapy. By the nature of medical work, exposures are expected to be non-uniform and the effective dose equivalent may not be easily obtainable from the dose indicated by a simple dosimeter, due to the energy or spatial inhomogeneity of the radiation field. The general situation, especially for diagnostic radiology, appears to be characterized by low annual average doses, often less than 1 mGy, to large numbers of workers. The only exception appears to be the use of sealed sources in radiotherapy where these are implanted or applied to the patient. There is evidence that doses are very greatly reduced by changing to techniques which do not require direct handling of the radiation sources, for example, after-loading techniques. It is not possible to identify and quantify the beneficial output of all medical work, although an attempt has been made to relate the doses from diagnostic radiology to the number of films processed. An indication of the total occupational exposure is expressed as the annual collective dose equivalent per million population of the country, on the grounds that total medical care should be roughly proportional to population. Even from the available data, it is clear that this measure varies considerably from one country to another, but a reasonable value to adopt for countries with a high standard of medical care seems to be about 1 man Sv per 10^6 population. A lower figure would be more appropriate for countries with a lower usage of radiation in medicine.

148. Other exposures to radiation in general industry have also been reviewed. Some anomalies are shown in exposure of industrial radiographers where a reasonably low average dose is reported, accompanied by a relatively high proportion of over-exposures. This situation needs closer investigation in detail by those with access to the individual dose results. Average doses to luminizers remain high, but the number of people involved is relatively small. The Committee has identified several special occupational groups on which more reported information in the appropriate detail would be highly desirable.

149. There are some other occupations in which, by virtue of the materials or surroundings, some increased exposure to radiation is incurred by workers. This radiation is generally of natural origin. The two major occupations falling into this category are air crew and non-uranium miners. There is a very large number of air crew exposed to enhanced cosmic ray dose rates and the average additional annual dose is now estimated as 1–2 mGy. Non-uranium miners are exposed in moderately large numbers to radon daughter levels which can be as high as those in uranium mines.

150. There is no clearly identified common output from industry and research and therefore the collective dose has been normalized to population. A reasonable estimate of the annual collective dose equivalent per million population from industrial and research uses of radiation is 0.5 man Sv per 10^6 population in industrialized countries; a considerably lower figure would be appropriate for developing countries. On the basis of the small amount of data available, the annual collective dose equivalent per million population from enhanced exposure to natural radiation, especially cosmic radiation while flying, is of the order of 1 man Sv per 10^6 population.

151. The Committee has reviewed the available data on accidental exposures to radiation. The objective was to identify those types of accident which occur most frequently and which give rise to clinical consequences. It is clear that most accidents are concerned with industrial uses of radiation rather than with the nuclear fuel

cycle. The overall number of accidents is very small when considering the large number of people using radiation or radioactivity in their work but the distribution of accidents between different types of work is highly non-uniform. Nonetheless there is one area of work, industrial radiography, in which the mishandling of sources and equipment, coupled with a high incidence of equipment failures, has led to a relatively large number of reported accidents with potentially serious consequences.

152. The Committee has made a number of suggestions concerning areas where more analysis of data is required to extract pertinent information. This could usefully be performed by those gathering the data. The Committee has also made suggestions regarding the level of detail which would be useful in reported data and the content of such reports. If these suggestions are acted upon there should be a very much clearer indication of the occupational exposure situation in some areas of work within a few years.

Table 1

An example of a distribution of annual individual doses within dose ranges for a nominal group of 1000 workers

Dose range (mGy)	Number of workers in the range	Cumulative frequency (%)	Collective dose in the range (man Gy) a/	Collective dose in the range (man Gy) b/	Fraction of collective dose above the range a/	Fraction of collective dose above the range b/
0 - 1	500	50.0	0.25	0.16	0.95	0.97
1 - 5	280	78.0	0.84	0.70	0.80	0.84
5 - 10	80	86.0	0.60	0.59	0.68	0.72
10 - 15	40	90.0	0.50	0.50	0.59	0.62
15 - 20	20	92.0	0.35		0.53	0.56
20 - 30	30	95.0	0.75		0.39	0.41
30 - 40	30	98.0	1.05		0.19	0.20
40 - 50	15	99.5	0.67		0.06	0.07
50 - 60	2	99.7	0.11		0.04	0.05
60 - 70	1	99.8	0.07		0.03	0.03
70 - 80	1	99.9	0.07		0.02	0.02
80 - 90	0	99.9	0		0.02	0.02
90 - 100	1	100	0.10		0	0
Total	1000		5.36	5.12		

a/ Calculated as the number of workers multiplied by the mid point dose.
b/ Calculated from the log-normal fit below 15 mGy in Figure I.

Table 2

Approximate exposures to radon daughters and calculated conversions to effective dose equivalent and collective effective dose equivalent for underground uranium miners in Canada, France and the United States in the late 1970s

Country	Approximate number of workers	Approximate annual average radon daughter exposures (WLM)	Approximate annual average effective dose equivalent (mSv)	Approximate annual collective effective dose equivalent (man Sv)
Canada [A1]	4000	0.75	6	25
France [B24]	1500	1.5	13	20
United States				
[C9]	3300	1.1	9	30
[R1]	5000	4.0	34	170

Table 3

Doses at fuel manufacturing plants in the United States (NRC Licensees) 1975-1978 [B1, B17, C1, U4]

Year	Number of workers monitored	Number of workers with measurable doses	Annual collective dose (man Gy)	Annual average dose (mGy): All those monitored	Annual average dose (mGy): Those with measurable doses	MR
1975	11614	5602	32	2.7	5.7	0.5
1976	11227	5285	18	1.6	3.5	0.4
1977	11496	7004	17	1.5	2.5	0.4
1978	11305	5896	14	1.2	2.4	0.3

Table 4

Doses in fuel fabrication and enrichment plants in the United Kingdom 1976-1978 [R2, U5, U16]

Process	Year	Number of workers	Annual collective dose (man Gy)	Annual average dose (mGy)	MR
Fuel enrichment	1976	570	0.40	0.7	0
	1977	598	0.35	0.6	0
	1978	706	0.36	0.5	0
Fuel fabrication	1976	2234	5.9	2.6	0.05
	1977	2484	6.3	2.5	0.03
	1978	2652	4.4	1.7	0.04

Table 5

Doses received by fuel manufacturing workers in Canada 1970-1978 [A1]

Year	Annual collective dose (man Gy)		Annual average dose (mGy)	
	Refining	Fabrication	Refining	Fabrication
1970	0.42	0.18	1.7	1.0
1971	1.68	0.31	6.6	1.6
1972	1.37	0.53	4.7	2.1
1973	2.12	0.84	6.2	2.9
1974	2.44	1.24	6.7	3.6 a/
1975	2.10	0.97	5.7	3.1 a/
1976	1.58	0.42	3.8	1.2
1977	0.68	0.69	1.4	1.8
1978	0.48	0.61	0.9	1.2

a/ Includes some estimated doses.

Table 6

Annual information reported on occupational exposure at BWRs in the United States 1973-1979 [B22]

Year	Number of workers with measurable doses	Energy generated in the year [GW(e) a]	Annual collective dose (man Sv)	Annual average dose to those with measurable doses (mGy)	Average number of workers with measurable doses per reactor	Collective dose per unit energy generated [man Gy (GW[e] a)$^{-1}$]
1973	5340	3.39	46	8.5	445	13
1974	8769	4.06	71	8.1	626	17
1975	14607	5.79	126	8.6	812	22
1976	17859	8.59	126	7.1	776	15
1977	21388	9.10	190	8.9	930	21
1978	20278	11.77	151	7.4	811	13
1979	25245	11.67	183	7.3	1010	16

T a b l e 7

Annual information reported on occupational exposure at PWRs in the United States 1973-1979 [B22]

Year	Number of workers with measurable doses	Energy generated in the year [GW(e) a]	Annual collective dose (man Sv)	Annual average dose to those with measurable doses (mGy)	Average number of workers with measurable doses per reactor	Collective dose per unit energy generated [man Gy $(GW[e] a)^{-1}$]
1973	9440	3.77	94	10.0	787	25
1974	9697	6.82	66	6.8	485	10
1975	10884	11.98	83	7.6	419	7
1976	17588	13.33	138	7.9	586	10
1977	20878	17.35	135	6.5	614	8
1978	25720	19.84	167	6.5	659	8
1979	38828	18.25	214	5.5	924	12

T a b l e 8

Annual collective dose and collective dose per unit energy generated at BWRs in various countries [F1, G3, I5, I6, I7, K2, M15, N1, P2]

Country	Year	Energy generated in the year [GW(e) a]	Annual collective dose (man Gy)	Collective dose per unit energy [man Gy $(GW[e] a)^{-1}$]
Japan a/	1975	0.80	41	51
	1976	1.19	50	42
	1977	0.74	61	83
	1978	1.62	115	71
Spain	1977	0.22	7	32
	1978	0.38	4	10
	1972-1978	0.33 b/	4 b/	12 b/
Sweden	1977	1.70	8	5
	1978	2.13	6	3
Switzerland	1977	0.19 c/	3	16
	1978	0.19 c/	3	16

a/ Including a GCR in Japan.
b/ Average over the 7-year period.
c/ Based on a 60 % load factor.

Table 9

Annual collective dose and collective dose per unit energy generated at PWRs in various countries [G3, G4, I5, I6, I7, I10, K2, M15, N1, P2, S1]

Country	Year	Energy generated in the year [GW(e) a]	Annual collective dose (man Gy)	Collective dose per unit energy [man Gy (GW[e] a)$^{-1}$]
German Dem.Rep.	1966-1978	3.9 a/		13 b/
Japan	1975	1.25	10	8
	1976	1.61	10	6
	1977	1.57	15	10
	1978	2.21	15	7
Spain	1977	0.14	1.5	11
	1978	0.12	3.9	32
	1970-1978	0.12 c/	1.7 c/	14 c/
Sweden	1977	0.47	2	4
	1978	0.47	2	4
Switzerland	1977	0.45 d/	5	11
	1978	0.45 d/	3	7

a/ Cumulative total over the 13-year period.
b/ Average over the 13-year period.
c/ Average over the 9-year period.
d/ Based on a 65 % load factor.

Table 10

Doses at nuclear power stations of the CANDU-PHW reactor type in Canada in 1977 [A1, N1]

Station	Installed capacity in 1977 [GW(e) a]	Annual average dose (mGy)	
		External	Internal (tritium)
Rolphton NPD 2	0.025	2.1	1.7
Douglas Point	0.22	3.3	3.5
Pickering A	2.17	4.7	4.4
Bruce A	2.34	0.6	0.2

Table 11

Annual collective dose per unit energy generated at nuclear power stations in Canada, 1972-1978 [A1, N1]

Year	Energy generated in the year [GW(e) a]	Annual collective dose per unit energy generated [man Gy (GW[e] a)$^{-1}$]
1972	0.8	15
1973	1.7	8
1974	1.7	5
1975	1.4	11
1976	2.0	7
1977	2.5	6
1978	3.5	5

Table 12

Doses at Atucha nuclear power station, Argentina, 1977-1979
[P20]

Year	Annual average dose (mGy)	Annual collective dose (man Gy)	MR	Collective dose per unit energy generated [man Gy (GW[e] a)$^{-1}$]
1977	16	10.0	0.8	56
1978	14	6.7	0.8	22
1979	17	9.0	0.8	32

Table 13

Doses at GCRs in the United Kingdom, 1975-1979
[G5, G6, G7, H2, H4, H18, P5, U3, U5]

Year	Number of workers	Annual average dose (mGy)	Annual collective dose (man Gy)	Collective dose per unit energy generated [man Gy (GW[e] a)$^{-1}$]
1975	6264	2.7	17	6
1976	6837	2.6	18	6
1977	9432	2.2	21	6
1978 a/	7025	2.3	16	5
1979 a/	6732	2.5	17	5

Table 14

Doses at the FBR Phenix, France, 1975-1979
[P9]

Year	Annual collective dose (man Gy)
1975	0.05
1976	0.08
1977	0.16
1978	0.08
1979	0.04

Table 15

Doses at FBR Dounreay, United Kingdom, 1974-1977
[A2]

Year	Annual average dose (πGy)	Annual collective dose (man Gy)
1974	1.2	0.3
1975	1.6	0.5
1976	1.8	0.6
1977	1.7	0.6

T a b l e 16

Doses in United States naval nuclear power ships, supporting tenders and submarine bases, 1970-1978 [M10]

Year	Number of workers	Annual average dose (mGy)	Annual collective dose (man Gy)	MR
1970	26980	1.1	31	0.1
1971	26813	1.2	33	0.3
1972	34108	1.0	33	0.3
1973	31570	1.0	32	0.3
1974	18749	1.1	21	0.2
1975	17997	1.2	22	0.2
1976	18229	1.4	26	0.2
1977	20716	1.4	28	0.3
1978	22403	1.0	22	0.2

T a b l e 17

Doses to naval shipyard workers in the United States associated with nuclear propulsion plants, 1970-1978 [M10]

Year	Number of workers	Annual average dose (mGy)	Annual collective dose (man Gy)	MR
1970	25923	5.0	131	0.8
1971	23925	4.4	106	0.7
1972	20199	3.5	70	0.6
1973	15252	4.0	61	0.6
1974	15157	4.8	72	0.6
1975	14663	3.6	53	0.6
1976	14973	3.5	53	0.5
1977	15723	3.3	52	0.5
1978	14984	2.5	37	0.4

T a b l e 18

Annual collective doses (man Gy) by work function at BWRs and PWRs in the United States, 1977-1979 a/ [B18, B22, P1]

Work function	1977	1978	1979
B W R s			
Operations	17	15	17
Maintenance	124	38	127
Supervision/Administration	19	13	13
Health physics	11	9	10
P W R s			
Operations	9	11	13
Maintenance	71	78	96
Supervision/Administration	12	16	20
Health physics	7	10	16

a/ The totals from this table are not the same as those in Tables 6 and 7, as some parts of the annual collective dose were not characterized by work function.

T a b l e 19

Percentage of the annual collective dose by work function for LWRs in several countries

Work function	German Dem. Republic [S1]	Fed.Rep.of Germany [U6]	Spain [F1]	Sweden [P2]	Switzerland [S2]
	1978	mid 1970s	1978	1978	1978
Operations	13	20	24	14	34
Maintenance	65 a/	80	65	72	57 a/
Supervision/ Administration	18 c/	b/	b/	6 c/	2 c/
Health physics	4	b/	11	8	7

a/ Including contractors.
b/ No values given.
c/ Including work categorized as "other".

T a b l e 20

Annual average and collective doses received by reactor workers in Canada, 1979 [A10]

Work function	Collective dose (man Gy)	Per cent of total collective dose	Annual average dose (mGy)
Operations		45	
Reactor operations	6.0		6.5
Fuel handling	0 a/		0.02
Control technician	3.2		5.1
Maintenance		47	
Electrical	0		0
Mechanical	7.7		11.5
General	1.1		1.4
General workers	0.7		1.1
Health physics		2	
Health physics	0.02		0.9
Chemical and radiation control	0.3		3.1
Administration/Supervision		6	
Administration, security, janitorial	1.2		0.9

a/ Less than 0.001 man Gy.

T a b l e 21

Collective doses received by workers at two GCRs in the United Kingdom [K3, K4]

Work function	Dungeness A (1977)		Wylfa (1978)	
	Collective dose (man Gy)	Per cent of total collective dose	Collective dose (man Gy)	Per cent of total collective dose
Operations	0.35	27	0.19	32
Maintenance	0.56	42	0.25	42
Administration/ Supervision	0.27	21	0.05	8
Health physics	0.13	10	0.11	18

Table 22

Doses at BNFL Windscale, 1976-1978
[U5, U16, R2]

Year	Number of workers	Annual average dose (mGy)	Annual collective dose (man Gy)	MR
1976	4406	11	49	0.7
1977	5055	10	48	0.7
1978	5722	8	48	0.7

Table 23

Annual collective dose per unit energy generated at BNFL Windscale, 1971-1978
[A4, C2, H5, H6, H7, R2, U5, U6]

Year	Annual collective dose per unit energy generated [man Gy (GW(e) a)$^{-1}$]
1971	12
1972	20
1973	13
1974	13
1975	15
1976	19
1977	28
1978	25

Table 24

Doses at Cap de La Hague, France, 1970-1979
[J3, P9]

Year	Number of workers	Annual average dose (mGy)	Annual collective dose (man Gy)	MR
1970	1140	2.3	2.6	0.3
1971	1187	2.9	3.5	0.4
1972	957	3.5	3.3	0.3
1973	1068	4.6	4.9	0.3
1974	1143	4.7	5.4	0.4
1975	1361	5.2	7.1	0.4
1976	1451	4.8	7.0	0.4
1977	1715	3.9	6.7	0.3
1978	1897	3.3	6.3	0.3
1979	1914	3.0	5.7	0.2

Table 25

Annual collective dose per unit energy generated at Cap de La Hague, France, 1972-1976
[C2, J3]

Year	Annual collective dose per unit energy generated [man Gy (GW(e) a)$^{-1}$]
1972	6
1973	9
1974	3
1975	5
1976	8

Table 26

Doses received by various groups of workers at reprocessing plants in France, 1974-1978 [B4]

Group	1974		1975		1976		1977		1978	
	Number of workers	Annual average dose (mGy)	Number of workers	Annual average dose (mGy)	Number of workers	Annual average dose (mGy)	Number of workers	Annual average dose (mGy)	Number of workers	Annual average dose (mGy)
Reprocessing	318	5.4	353	5.4	377	4.7	420	4.4	503	3.8
Decontamination	218	7.1	241	7.9	195	9.7	311	6.2	296	6.2
Maintenance	328	3.3	433	4.8	456	4.7	558	4.0	543	3.1
Chemical and electrical technicians, health physics	173	1.7	177	1.7	188	1.8	226	1.6	283	1.5

Table 27

Doses at the Eurochemic Fuel Reprocessing Plant at Mol, Belgium, 1970-1978 [O1]

Year	Number of workers	Annual average cose (mGy)	Annual collective dose (man Gy)	MR
1970	268	13	3.4	0.8
1971	285	11	3.2	0.8
1972	235	18	4.3	0.8
1973	225	16	3.7	0.8
1974	187	14	2.7	0.8
1975	169	9	1.6	0.7
1976	175	8	1.5	0.7
1977	180	10	1.7	0.6
1978	212	11	2.2	0.3

Table 28

Doses at the Fuel Reprocessing Plant at Karlsruhe, Federal Republic of Germany, 1972-1978 [S5]

Year	Number of workers	Annual average dose (mGy)	Annual collective dose (man Gy)
1972	216	13	2.9
1973	241	11	2.7
1974	284	5	1.4
1975	325	2	0.6
1976	311	3	1.0
1977	318	4	1.4
1978	373	5	1.7

Table 29

Doses to workers in nuclear research and development in the United States, 1975-1979 [U8, U9, U17, U18, U19]

Year	Number of workers with measurable dose	Annual average dose (mGy)	Annual collective dose (man Gy)	MR
1975	34428	3	96	0.4
1976	40802	2	88	0.3
1977	40660	2	87	0.3
1978	43647	2	77	0.3
1979	41881	2	73	0.3

Table 30

Doses at Atomic Energy of Canada Ltd. sites, 1970-1978 [M8]

Year	Number of workers with measurable exposure		Annual average dose (mGy)		Annual collective dose (man Gy)	
	External	Tritium	External	Tritium	External	Tritium
1970	1334	412	11	1.7	15	0.7
1971	1439	480	8.2	1.9	12	0.9
1972	1527	483	8.5	1.8	13	0.8
1973	3677	187	2.8	1.5	10	0.3
1974	3758	347	3.0	1.3	11	0.5
1975	3615	320	3.0	1.2	11	0.4
1976	3554	315	3.3	1.9	12	0.6
1977	3565	341	3.5	1.8	13	0.6
1978	3902	389	3.4	2.5	13	1.0

Table 31

Doses at United Kingdom research and development establishments connected with the nuclear power industry, 1975-1979 [G6, G7, H18, T1, U16]

Organization	Year	Annual average dose (mGy)	Annual collective dose (man Gy)	MR
United Kingdom Atomic Energy Authority	1975	5.5	41	0.2
	1976	5.8	44	0.3
	1977	4.3	34	0.2
Central Electricity Generating Board, Berkeley Nuclear Laboratories	1975	1.1	0.7	0.2
	1976	1.2	0.7	0.1
	1977	1.3	0.9	0
	1978	0.9	0.6	0.1
	1979	1.1	0.8	0

Table 32

Doses at Karlsruhe Nuclear Research Centre, Federal Republic of Germany, 1970-1978
[K5]

Year	Number of workers	Annual average dose a/ (mGy)	Annual collective dose a/ (man Gy)
1970	2785	0.6	1.8
1971	2992	0.7	2.1
1972	2894	1.3	3.8
1973	3096	1.3	4.1
1974	2841	1.2	3.4
1975	2782	0.7	2.0
1976	3000	0.8	2.3
1977	3157	0.8	2.4
1978	3194	0.8	2.5

a/ With natural background assumed to be 0.82 mGy a^{-1} subtracted.

Table 33

Doses received by different groups of workers at Karlsruhe Nuclear Research Centre, Federal Republic of Germany, 1975-1978
[K5]

Group	Annual average dose (mGy) a/			
	1975	1976	1977	1978
Waste handling	7.2	5.3	4.5	4.2
Health physics	3.0	2.7	2.7	2.9
Cyclotron	1.8	1.9	2.7	3.9
Reactor	1.8	1.9	1.4	1.5
Chemistry	0.9	1.9	1.6	1.6
Supply service	0.5	0.4	0.3	0.4
Physics	0.1	0	0.1	0.2
Biology	0	0	0.1	0.3
Others	0	0	0.1	0

a/ With natural background assumed to be 0.82 mGy a^{-1} subtracted.

Table 34

Doses to nuclear research and development workers in various countries
[D1, G3, G8, K2, M15, P3, P20]

Country	Year	Number of workers	Annual average dose (mGy)	Annual collective dose (man Gy)	Collective dose per unit energy generated [man Gy (GW[e] a)$^{-1}$]
Argentina	1977	476	1.3	0.6	
	1978	525	1.2	0.6	3 a/
	1979	700	0.9	0.6	
	1980	516	1.2	0.6	
Belgium	1976	1427	3.8	5.4	
(Mol)	1977	1444	1.9	2.8	3
	1978	1469	1.9	2.8	
Japan (Atomic Energy Industry) b/	1978	17800	0.2	4.2	1
Switzerland	1976	294	2.6	0.8	
(Reactor	1977	360	2.8	1.0	1
Research Institute)	1978	351	2.4	0.8	

a/ This figure would be 7 man Gy [GW(e) a]$^{-1}$ if doses due to non-nuclear power research and development at the same sites had been included [P20].
b/ Numbers extrapolated from a survey estimated to cover 50 % of workers.

Table 35

Contribution to the collective dose equivalent per unit energy generated in the nuclear fuel cycle

Part of the cycle	Collective dose equivalent per unit energy generated [man Sv (GW[e] a)$^{-1}$]
Mining and milling	1
Fuel manufacture	1
Reactors	10
Reprocessing	10
Research and development	5
Total	27

Table 36

Doses to workers in medicine using radionuclide sources under NRC Licenses in the United States, 1978 [B17]

Category of licensee	Number of workers with measurable dose	Annual average dose (mGy)	Annual collective dose (man Gy)	MR
Institutions				
- broad	10570	1.5	16	0.2
- others	24660	2.5	63	0.2
Private practice	1620	3	5	0.1
Teletherapy	1570	2	3	0.3
Other	410	1	0.4	0.1

Table 37

Doses to medical workers in the United States monitored by the Bureau of Radiological Health, 1972-1978 [M9]

Year	Number of workers	Annual average dose (mGy)	Annual collective dose (man Gy)
1972	3874	0.5	2.1
1973	3843	0.5	2.0
1974	3829	0.5	2.1
1975	4017	0.8	3.2
1976	4549	0.9	4.3
1977	5048	0.4	1.8
1978	5483	0.3	1.7

Table 38

Doses received by some groups of medical workers in the United States monitored by the Bureau of Radiological Health, 1972-1978 [M9]

Group	Annual average dose (mGy)						
	1972	1973	1974	1975	1976	1977	1978
Radiologists	1.2	0.7	1.1	3.6	3.2	1.3	1.7
Other physicians	0.4	0.3	0.5	0.8	0.9	0.3	0.3
x-ray technicians	0.8	0.7	0.9	1.6	1.4	0.7	0.5
Other technicians	0.4	0.3	0.4	0.6	1.6	0.3	0.3

Table 39

Doses to medical workers in Switzerland, 1976-1978 [P3, P7, P8]

Group	Year	Number of workers	Annual average dose (mGy)	Annual collective dose (man Gy)	MR
Hospitals	1976	6259	0.5	2.9	0.3
	1977	7164	0.5	3.9	0.2
	1978	7641	0.6	4.2	0.1
General practice	1976	6059	0.1	0.8	0.1
	1977	6901	0.1	1.0	0.02
	1978	8185	0.2	1.3	0.1
Radiologists	1976	182	0.8	0.1	0.1
	1977	193	0.9	0.2	0
	1978	439	0.6	0.3	0.2

Table 40

Doses to medical workers using x rays for diagnosis in France, 1976-1979 [P9, S17]

Group	Year	Number of workers	Annual average dose (mGy)	Annual collective dose (man Gy)	MR
Private general medicine	1976	759	2.5	1.9	0.1
	1977	804	1.1	0.9	0.2
	1978	841	2.5	2.1	0.1
	1979	901	1.0	0.9	0.1
Private special clinics	1976	2259	2.0	4.5	0.2
	1977	2421	1.5	3.6	0.2
	1978	2532	1.7	4.3	0.2
	1979	2731	1.6	4.4	0.1
Private radiology	1976	1446	2.2	3.2	0.2
	1977	1534	2.6	4.0	0.2
	1978	1568	2.3	3.6	0.1
	1979	1845	1.7	3.1	0.1
Industrial medicine	1976	4731	1.1	5.2	0.1
	1977	4699	1.0	4.7	0.1
	1978	4444	0.3	1.3	0.2
	1979	4403	0.4	1.8	0.1
Hospitals	1976	10309	1.7	18	0
	1977	11600	1.3	15	0.2
	1978	13106	1.2	16	0.1
	1979	14973	0.8	12	0.1

Table 41

Doses to medical workers assumed to be mainly involved with diagnostic radiology in various countries [A10, F2, I9, M15, S19, W2]

Country	Description of work	Year	Number of workers	Annual average dose (mGy)	Annual collective dose (man Gy)
Australia a/	Hospital radiology	1978	520	1.2	0.6
	Private radiology		100	2.3	0.2
	General practice		170	0.2	0.03
	Radiography		2700	0.8	2.1
	Assistants, nurses, etc.		1000	0.5	0.5
Canada	Radiologists	1979	1354	0.4	0.6
	Radiological technicians		7380	0.2	1.8
	Physicians		1478	0.4	0.5
	Nurses		2993	0.4	1.0
Germany, Fed.Rep.of	Medical workers	1976	101500	0.4	45
		1977	118449	0.4	53
Israel	Medical workers	1975	1860	1.0	2
Japan a/ b/	Doctors	1978	40800	0.6	23
	Technicians		28600	0.8	23
	Nurses		21700	0.3	7.4
	Other		9600	0.3	2.6
Other Asia	Medical workers	1975	1300	1.7	2.3

a/ Numbers extrapolated from a survey estimated to cover 50 % of workers.
b/ Workers with x rays and gamma rays.

Table 42

Comparison of medical occupational doses with medical practice [E1, M15, T1, U3]

Country	Estimated annual collective dose equivalent to all medical workers (man Sv)	Number of films used for x-ray examinations per year (10^6)	Annual collective dose equivalent per film to medical workers (10^{-6} man Sv per film)
German Dem. Rep.	11	11	1.0
Germany,Fed.Rep.of	50	100	0.5
India	9	19	0.5
Japan	78	120	0.7
Sweden	22	5.3	4.2
Switzerland	7	8.5	0.8
United Kingdom	70	40	1.8
United States	270	130	2.1
Other Asia	2.5	0.7	3.6

Table 43

Doses to dental workers in various countries
[A10, C1, P3, P7, P8, P9, S19]

Country	Description of work	Year	Number of workers	Annual average dose (mGy)	Annual collective dose (man Gy)
Australia a/	Dentists, nurses and assistants	1974	2000	0.1	0.2
		1978	1600	0.1	0.2
Canada	Dentists	1979	4028	0.05	0.2
France	Dental stomatology	1976	3952	0.5	2.0
		1977	4751	0.4	1.9
		1978	5399	0.3	1.6
		1979	6382	0.5	3.2
Switzerland	Dental practice	1976	6634	0.2	1.4
		1977	7026	0.2	1.0
		1978	7683	0.2	1.2
United States	Dental practice	1975	265000	0.2	53

a/ Numbers extrapolated from a survey estimated to cover 50 % of workers.

Table 44

Doses to workers in nuclear medicine in Australia and France
[P9, S19]

Country	Description of work	Year	Number of workers	Annual average dose (mGy)	Annual collective dose (man Gy)
Australia a/	Nuclear radiographers and assistants	1974	960	0.8	0.8
		1978	930	0.4	0.4
France	Nuclear medicine	1976	2105	1.7	3.6
		1977	2275	0.9	2.0
		1978	2215	1.5	3.3
		1979	2453	0.5	1.2

a/ Numbers extrapolated from a survey estimated to cover 50 % of workers.

Table 45

Doses to workers in radiotherapy in various countries
[C1, P9, S19]

Country	Description of work	Year	Number of workers	Annual average dose (mGy)	Annual collective dose (man Gy)
Australia	Dermatologists	1978	60	1	0.06
	Radiologists and gynaecologists		40	2	0.08
	Radiographers and hospital physicists		350	1	0.4
France	Conventional radiotherapy	1976	947	1.7	1.6
		1977	1005	1.3	1.3
		1978	937	1.4	1.3
		1979	880	1.5	1.3
	Cobalt therapy	1976	1255	2.4	3.0
		1977	1310	2.6	3.4
		1978	1442	2.6	3.7
		1979	1564	1.3	2.0
	High energy therapy	1976	656	1.0	0.7
		1977	727	2.3	1.7
		1978	791	1.4	1.1
		1979	864	0.8	0.7
United States	All therapy a/	1975	20000	3	60

a/ Numbers extrapolated from returns from NRC Licensees [C1].

Table 46

Annual collective dose equivalents in the mid to late 1970s from occupational exposures connected with medical practice, normalized to population [A10, C1, E1, F2, I9, M15, P3, P7, P8, P9, T1, U3, W2]

Country or area	Estimated collective dose equivalent (man Sv)	Number of workers	Population (10^6)	Annual collective dose equivalent per 10^6 population (man Sv per 10^6 population)
Canada	8	32000	24	0.3
France	45	38000	53	0.8
German Dem.Rep.	10	a/	17	0.6
Germany,Fed.Rep.of	50	110000	61	0.8
India	9	a/	600	0.02
Israel	2	1900	4	0.5
Japan	78	110000	116	0.7
Sweden	22	a/	8	2.8
United Kingdom	70	33000	55	1.3
United States	270	100000	210	1.3
Other Asia	3	1300	17	0.2

a/ Not reported.

Table 47

Doses to industrial radiographers in various countries [A10, B17, C1, C4, M15, P9, S17, S19]

Country	Description	Year	Number of workers	Annual average dose (mGy)	Annual collective dose (man Gy)	MR
Australia a/	Users of open installations, including industrial radiographers	1974	850	2.4	2.0	-
		1978	750	1.3	1.0	-
	Users of enclosed installations, or quality control sources	1974	870	0.1	0.1	-
		1978	780	0.1	0.1	-
Canada	Industrial radiography	1979	1061	3.3	3.5	
France	Industrial radiography	1976	1091	1.5	1.6	0
		1977	1203	1.3	1.6	0
		1978	1351	0.9	1.2	0.1
		1979	1436	1.1		
Japan a/	Non-destructive inspection	1978	3670	1.2	4.3	-
United States (NRC licensed)	Industrial radiography	1974	8792	3 b/	29	0.5
		1975	9178	3 b/	28	0.5
		1976	11245	3 b/	36	0.5
		1977	10569	3 b/	32	0.4
		1978	13093	2 b/	30	0.4
(non-NRC licensed)	Radiography	1970-1975	4300	2	7	0.5
	Analysis		600	0.1	0.1	
	Mixed and other		1700	2	3	0.4

a/ Numbers extrapolated from a survey estimated to cover 50 % of all workers.
b/ Annual average dose to all those monitored; the average to those with measurable doses is in the range 4-6 mGy.

Table 48

Doses to luminizers in various countries
[A10, P3, P7, P8, P9, T1]

Country	Description	Year	Number of workers	Annual average dose (mGy)	Annual collective dose (man Gy)	MR
Canada	Dial painters	1979	3	0.1	< 0.001	0
France	Tritium luminizers	1976	80	3.5	0.3	0.6
		1977	71	4.7	0.3	0.6
		1978	63	6.6	0.4	0.7
		1979	69	6.8	0.5	0.7
Switzerland	Luminizers	1976	208	11	2.2	0.4
		1977	221	11	2.5	0.5
		1978	232	12	2.8	0.6
United Kingdom	Gas luminizers	1975	49	15	0.7	0.7
		1976	41	16	0.7	0.8
	Paint luminizers	1975	97	4	0.4	0.5
		1976	88	5	0.4	0.2

Table 49

Doses to some identified industrial users of radiation in various countries
[A10, B17, R6, S19]

Country	Use description	Number of workers	Annual average dose (mGy)	Annual collective dose (man Gy)	MR
Australia (1978) a/	X-ray analysis, electron microscopy etc.	660	0.1	0.1	-
	Radioactive tracers	720	0.5	0.4	-
	Installation and maintenance engineers	200	0.2	0.05	-
Canada (1979)	Well loggers	685	1.4 b/	1.0 b/	0.1
	Instrument technicians	675	0.4	0.3	0.2
	Laboratory technicians	1790	0.3	0.5	0
	Field scientists/engineers	484	0.7	0.4	0.1
United States (1978)	Well logging	6380	2.7 b/	17 b/	0.3
	Other measuring systems	24720	0.3	6.5	0.1
	Leak test	150	0.7	0.1	0.2
UkSSR	Borehole loggers (neutron sources)	95	5.0 b/	4.9 b/	0.3

a/ Numbers extrapolated from a survey estimated to cover 50 % of workers.
b/ Annual average dose equivalent (mSv) and collective dose equivalent (man Sv) including a contribution from neutrons.

T a b l e 50

Doses to research workers in the United States, 1974-1978
[B17, U7, U8, U9, U17, U18]

Category	Number of workers with measurable dose	Annual average dose (mGy)	Annual collective dose (man Gy)	MR
DOE and DOE Contractors, 1978				
Academic				
Broad	4110	1.3	5.6	0.1
Other	2930	1.2	3.6	0.1
Research and development				
Broad	2361	1.1	2.7	0.2
Other	2120	0.7	1.6	0
Irradiators < 370 TBq	310	1.1	0.4	0.1
Irradiators > 370 TBq	630	1.6	1.0	0.1
Uses of special nuclear material				
Uranium sources	30	2.2	0.1	0.6
Unencapsulated sources	20	9.9	0.2	0.6
Neutron source	530	1.1 a/	0.6 a/	0.2
Other uranium uses	350	2.0	0.7	0.3
DOE Contractors				
Accelerators, 1976	1384	4.8	6.7	0.5
1977	1692	4.7	7.9	0.5
1978	1579	3.6	5.7	0.4
ERDA Contractors				
Accelerators, 1974	2357	4.8	11.3	0.6
1975	2382	4.5	10.7	0.6

a/ Annual average dose equivalent (mSv) and collective dose equivalent (man Sv) including a contribution from neutrons.

T a b l e 51

Doses to research workers in various countries
[F2, I9, M15, P3, P7, P8, P9, T1, W2]

Country or area	Work description	Year	Number of workers	Annual average dose (mGy)	Annual collective dose (man Gy)	MR
Canada	Laboratory scientists	1979	1575	0.3	0.4	0
	Other		2310	0.5	1.0	0
France	Research workers	1976	1729	0.8	1.4	0
		1977	2000	0.9	1.8	0
		1978	2398	0.5	1.2	0
		1979	2856	0.2	0.6	0
Germany, Fed.Rep.of	Research workers	1976	10169	0.4	4.6	-
		1977	12689	0.6	8.0	-
Israel	Research workers	1975	1393	0.3	0.4	-
Japan	Research and education	1978	20000	0.04	0.8	-
Switzerland	Research workers	1976	5046	1.1	5.7	0.2
		1977	6429	0.9	5.6	0.3
		1978	8838	0.7	6.2	0.3
United Kingdom	Research, mainly university	1977	11000	2.5	27	0
Other Asia	Research workers	1975	187	0.4	0.1	0

Table 52

Annual collective dose equivalents in the mid and late 1970s from occupational exposure connected with industry and general research normalized to population
[A10, B17, F2, I9, P3, P7, P8, P9, T1, W2]

Country or area	Estimated collective dose equivalent (man Sv)	Number of workers	Population (10^6)	Annual collective dose equivalent per 10^6 population (man Sv per 10^6 population)
Canada	7	8500	24	0.3
France	7	9000	53	0.1
Germany, Fed.Rep.of	50	25000	61	0.8
Israel	1	2000	4	0.3
Switzerland	10	10000	15	0.7
United Kingdom	35	12000	55	0.6
United States	100	110000	210	0.5
Other Asia	1	1100	17	0.06

Table 53

Accidents to workers in the nuclear industry 1945-1979

Year	Description of accident	Dose	Clinical effects
1945	USA. Worker at Los Alamos stacking tungsten carbide bricks around plutonium core accidentally made the system critical. He remained to unstack the assembly. Army guard also exposed [S10, T3]	Total body doses (1) 3 Gy n and γ (2) 1.18 Gy n, 0.02 Gy γ	(1) Vomiting and nausea within 2 h, fever, hair loss, death after 25 days. (2) Some weakness after 60 days.
1946	USA. Worker at Los Alamos was demonstrating the creation of a critical assembly when beryllium shell fell into assembly; six others were exposed [S10, T3]	Total body doses (1) 12 Gy n, 1.2 Gy γ (2) 2.2 Gy n, 0.2 Gy γ (3) 1.2 Gy n, 0.12 Gy γ (4) 0.5 Gy n, 0.05 Gy γ (5) 0.3 Gy n, 0.03 Gy γ (6) 0.25 Gy n (7) 0.25 Gy n, 0.02 Gy γ	(1) Vomiting within 1 h, GI syndrome, fever, death after 9 days. (2) Nausea and vomiting within 6 h, fever, epilation.
1953 or 1954	USSR. Criticality accident at a reactor [G10, T3]	Total body doses (1) 3 Gy; (2) 4.5 Gy	(1) and (2) Nausea and vomiting within 1 h, fever, infection, weakness.
1958	USA. Criticality accident at Oak Ridge in an area where soluble enriched uranium was recovered, as a result of the inadvertent accummulation of aqueous enriched uranium solution in a vessel [C6, H10, A6]	Total body doses (1) 3.7 Gy; (2) 2.7 Gy (3) 3.4 Gy; (4) 3.3 Gy (5) 2.4 Gy; (6) 0.7 Gy (7) 0.7 Gy; (8) 0.2 Gy)	(1)-(5) Nausea after 2-48 h, vomiting (4 only) lymphocytes fell within 48 h and serious depression of white cells and platelets 25-30 days after the accident.
1958	Yugoslavia. Experimental reactor of Vinca became uncontrolled when the amount of heavy water moderator was abnormally increased [A7]	Total body doses (1) 4.36 Gy; (2) 4.14 Gy (3) 4.26 Gy; (4) 4.19 Gy (5) 3.23 Gy; (6) 2.07 Gy	Nausea, depression of white cells and platelets, haemorrhages. (1) died after 4 weeks (1)-(5) bone marrow transplants.
1958	USA. Criticality excursion at the plutonium recovery plant at Los Alamos occurred when excess plutonium was washed into a large vessel. The excursion occurred when the operator started a stirrer. Two other operators exposed to help their colleague [S11]	Total body doses (1) 45 Gy; (2) 1.3 Gy (3) 0.35 Gy	(1) Neurological syndrome, coma within 10 min, erythema, virtual disappearance of lymphocytes with 6 h, death from cardiac failure after 35 h. (2) and (3) Lymphocyte depression
1961	USA. Nuclear excursion at SL-1 reactor at Idaho probably due to an excessive withdrawal of the central control rod. Hot water expelled violently from core [C7, P11]	Total body doses (1) 0.3-78 Gy (2) 19-100 Gy (3) 350 Gy	All died as a result of the explosion.
1962	USA. Criticality excursion at Hanford plant when excess plutonium bearing waste was added to a small tank [F3]	Total body doses (1) 0.63 Gy γ; 0.2-0.3 Gy n (2) 0.23 Gy γ;0.09-0.12Gy (3) 0.13 Gy γ; 0.03 Gy n	(1) Fever, depression of lymphocytes.
1964	USA. Criticality excursion at Wood River Junction uranium recovery plant. Technician poured concentrated liquor into a tank, mistaking it for slightly contaminated trichloroethane. Second excursion occurred when tank stirrer was turned off exposing two supervisors [A8, P12]	Total body dose (1) 12-46 Gy n (2) 0.06-0.2 Gy n (3) 0.28 Gy n	(1) GI prodrome within minutes, death after 46 h.

Table 53, continued

Year	Description of accident	Dose	Clinical effects
1965	Belgium. Nuclear excursion in experimental reactor during manual displacement of control rods [B9, N2]	Dose to left foot 39 Gy γ, 4.2 Gy n Dose to abdomen 0.5-8 Gy Dose to head > 3 Gy	GI prodrome, haematological depression, reverse barrier nursing bone marrow transplant, fever, necrosis and amputation of left foot.
1968	UK. Scientist handled highly active fuel element section [P13]	Total body dose 0.15 Gy	Burns on thumb and two fingers on right hand.
1976	USA. Worker injured by the chemical explosion of an ion exchange column used for americium recovery at Hanford [H12]	Dose up to 1978 bone 8.6 Gy; lung 2.0 Gy; liver 1.6 Gy; Dose to bone expected to continue at 10 mGy d^{-1}	Ulcer near right eyebrow. Some depression of lymphocytes. Patient decontaminated and treated with DTPA.

Table 54

Accidents to workers in non-nuclear industry (excluding industrial radiography) 1960-1979

Year	Description of accident	Dose	Clinical effects
1960	USA. Worker exposed to an electron beam [U12]	Dose to face 7.6 Gy	Multiple burns to middle section of face, abdomen and hands
1965	USA. Worker entered room where linear accelerator was scanning products on conveyor belts with an electron beam by going under the barrier. He placed a mould on the conveyor belt near the output port of the accelerator [L5]	Dose estimates Interior of body 0.002-0.05 Gy Anterior and right surface 2.4-3.3 Gy Eyes 0.43 Gy Right toes 110 Gy Right instep 290 Gy Right 5th digit 420 Gy Right thumb 2400 Gy	Erythema on right hand and foot within 4 h. Right arm amputated above elbow. Right leg amputated above knee
1965	USA. Two operators exposed to radiation from a fluoroscope with a broken interlock [V2]	Not quoted	Burns on hands
1967	India. Cobalt-60 teletherapy source jammed during transfer. Operator, wearing lead gloves, inserted source manually [B12]	Dose to skin approximately 80 Gy	Burning and blisters on one hand
1967	USA. Operator bypassed interlocks and energized a fluoroscope during cleansing [V2]	Not quoted	Several burns to exposed parts of body
1969	USA. Two service engineers bypassed safety circuits and energized a spectrometer	Not quoted	Burns on hands
1970	USA. Factory worker exposed hands when he failed to observe that warning light on unit (unspecified) was on [V2]	Not quoted	Burns on hands
1971	USA. Two factory workers exposed to radiation from a fluoroscope [V2]	Not quoted	(1) Blistering on right index fin (2) Burns and blisters covering both hands and open lesions on three fingers on each hand
1971	USA. Operator exposed to 300 TBq cobalt-60 source at an irradiation facility when he entered the room while the source was exposed [V3, P16]	Total body dose 1.27 Gy Dose to right hand 2-12 Gy	Vomiting, haematological depression, pain in fingers and palm of right hand
1971	USA. Factory worker's hands were exposed to the beam from fluoroscope which still emitted x rays with the top open because of faulty wiring [V2]	Not quoted	Erythema on hands
1971-1972	UK. Engineer servicing x-ray equipment received high dose to fingers on three occasions [P17]	Dose to fingers several hundred Gy	Small burn on fingers
1972	UK. Engineer servicing x-ray crystallography equipment at a Technical College exposed to a narrow beam of x rays because the shutter had been removed [L7, P15]	Dose to two fingers 15-20 Gy	Burn, which subsequently healed, on two fingers
1974	USA. Operator entered cobalt-60 irradiation cell believing that the 4 PBq source was in its storage pool [S14]	Total body dose 1.65-4 Gy	Vomiting, depression of haemopoietic system. In reverse isolation for 6 weeks

Table 54, continued

Year	Description of accident	Dose	Clinical effects
1974	USA. Three workers exposed to x rays from a quantometer when the beam inadvertently remained on during maintenance [V2]	Nct quoted	(1) and (2) Burns on hands (3) required hospitalization
1974	USA. Serviceman exposed to x rays from a research spectrometer when his partner accidently energized the tube [V2]	Not quoted	Erythema on right hand
1975	Italy. Worker exposed to cobalt-60 radiation at an agricultural installation [N2, L8]	Total body dose 10 Gy	Death
1976	USA. Worker exposed to radiation from an x-ray analyser while making a repair when the unit was on [V2]	Not quoted	Burns on fingers
1976	USA. Operator exposed while cleaning the vacuum x-ray quantometer because the microsafety switch failed as a result of faulty wiring [V2]	Not quoted	Burns on right hand and finger
1977	USA; Operator entered cobalt-60 irradiation cell while the 20 PBq source was exposed. The interlock system had been deactivated [S15]	Total body dose 2 Gy	Nausea, hair loss, light erythema, depression of haemopoietic sustem, kept in reverse isolation
1977	USA. Operator exposed fingers while attempting to adjust lead aperature diaphragm on a diffractometer [V2]	Not quoted	Burns on 2 fingers
1977	USA. Repairman exposed during check of vacuum leak on a spectrometer as a result of failure of automatic cut-off switch [V2]	Not quoted	First degree burns to face and finger tips
1978	USA: Operator of a fluoroscope at a soup company exposed when relay on the door interlock fused [V2]	Not quoted	Pigmentation on back of hand

Table 55

Accidents to workers in industrial radiography 1960-1979

Year	Description of accident	Dose	Clinical effects
1960	USSR. A demented person placed a caesium-137 source in his trouser pocket [D4]	Total body dose 14.8 Gy Maximum dose to skin 1650 Gy	GI prodrome after 7 h, necrotic skinlesions, death after 18 d.
1967	USA. Two radiographers exposed when 2.6 TBq source became disconnected from its control cable [M13]	(1) Total body dose 0.2 Gy Dose to right hand 40-60 Gy (2) Total body dose 0.15 Gy	(1) Hand oedema, formation of vesicles, slight atrophy of finger
1968	Argentina. Worker carried 0.5 TBq caesium-137 source in his trouser pockets for 18 h [B14]	Total body dose 0.5 Gy Maximum skin dose to thighs 17000 Gy Dose to gonads 20 Gy	Necrotic lesions on thighs, desquamated surface of scrotum and base of penis. Ulcers on right hand. Both legs amputated
1968	FRG. Worker carried iridium-192 source in jacket pocket [S16]	Total body dose 1 Gy Maximum dose to pelvis and thigh 40-60 Gy	Aspermia Inflammatory skin alterations
1968	India. Worker picked up a 52 GBq iridium-192 source which had fallen from a radiography camera and kept it in his pocket for 2 h [A9]	Dose skin near source 130 Gy Dose to testes 1.3 Gy	Ulcer wound took a year to heal completely. Sterility 2 years
1969	UK. Radiographer exposed to gamma-radiation from a 0.9 TBq iridium-192 source while travelling in a car with the source housing open. Also believed to have placed a source in his breast pocket for a short while. Both occurrences denied by individual [H16]	Total body dose 0.6 Gy Dose to small area of chest 20-200 Gy Dose to wrist,finger tips 15 Gy	Chest inflammation, blistering necrotic tissue, involving ribs and heart. Skin graft required, left wrist and finger tips lesions and blistering
1970	UK. Worker exposed while carrying a 0.8 TBq iridium-192 source up a ships ladder with the container open [P13]	Dose to irradiated area not quoted Dose at chest level 300 μGy	Erythema on thighs, septic spot and reddish mottling

Table 55, continued

Year	Description of accident	Dose	Clinical effects
1971	Japan. Construction worker found an iridium-192 source in a shipyard and took it back to his lodging. Five other people were exposed during the 8 d before it was recognized. Some handled the source [K7]	Total body dose (1) 1.3-1.5 Gy; (2) 0.5 Gy (3) 0.1-0.4 Gy; (4) 0.2-0.25 Gy; (5) 0.13-0.17 Gy (6) 0.15-0.16 Gy; (2) Maximum dose to skin of hip 30-60 Gy (1, 2, 3) Dose to skin of hands 26-90 Gy	(1) GI prodrome (1, 2, 3) skin lesions, lesions on hip of (2) removed surgically (1, 2, 3, 4) depression of blood cells
1971	UK. Worker handled 0.2 TBq iridium-192 source [P15]	Dose to finger 30 Gy	Burns on finger tips
1972	FRG. Worker at Bremen exposed to a 1.1 TBq iridium-192 source [S20, S21].	Total body dose 0.3 Gy Dose to hand 50 Gy	Erythema and moist desquamation. Necrosis followed by amputation of finger
1974	Middle East. Radiographer exposed when iridium-192 source became detached and lodged in the delivery tube for 2-3 d [P18]	Total body dose 0.3 Gy	Pain and swelling in leg and loss of hair
1975	Iraq. Radiographer exposed to 2.3 TBq iridium-192 source [L10]	Total body dose 0.27 Gy	Burns on several fingers
1976	USA. Radiographer approached and unscrewed source tube while the 3.5 TBq iridium-192 was not fully retracted into its shield [U13, U4]	Total body dose 0.05 Gy Dose to hand 4.48-37.21 Gy	Erythema and thickening of skin on palm of right hand
1976	USA. Radiographer touched a guide tube containing an unshielded 6.1 TBq cobalt-60 source. He had overridden the radiation alarm system [U13, U4]	Dose to hand 15 Gy Dose to lens 0.09 Gy	Erythema and dry desquamation of left hand
1977	UK. Radiographer working in a confined space held a 0.8 TBq iridium-192 source with his finger tips for 90 s whilst radiographing a weld [L9]	Total body dose 0.1 Gy	Burns on three fingers
1977	South Africa. Maintenance engineer picked up a 0.25 TBq iridium-192 source from a factory floor without recognizing it. He showed it to several colleagues and took it home. Doses to three most exposed individuals given [L9, B16]	Total body dose (1) 1.16 Gy; (2) 0.17 Gy (3) 0.1 Gy Maximum skin dose (1) 50-100 Gy	(1) Burns on chest and hands, skin graft on chest

Table 56

Accidents to workers in research and development (excluding nuclear industry) 1960-1979

Year	Description of accident	Dose/activity	Clinical effects
1960	USA. Graduate student exposed to a 7 TBq cobalt-60 source when it became detached during irradiation of samples [R5]	Total body dose 2.5-3 Gy Maximum dose to skin 30 Gy	GI prodrome, depression of white cell count, necrotic lesion on stomach, sterility
1965	USA. Researcher assumed diffractometer was off, removed shielding and reached inside to change samples [V2]	Not quoted	Burns to three fingers
1965	USA. Chemist exposed to primary beam of spectrometer when interlocks failed [V2]	Not quoted	Burns to fingers
1967	USA. Technician exposed for 20 min to the beam of a Van de Graff generator [V2]	Not quoted	Nausea, amputation of legs and arms
1970	Australia. Three workers exposed to low energy radiation from a wrongly assembled x-ray analysis unit [L11]	Dose to skin (1) Abdomen 15-45 Gy; Hands 20 Gy (2) Arm 4-15 Gy; Hands 15 Gy (3) 0.14-0.5 Gy	(1, 2) Erythema and dry desquamation (3) No clinical symptoms
1970	USA. Scientist removed valuable specimen from spectrometer bypassing interlocks because he feared he would lose it [V2]	Not quoted	Moderate conjunctive infection, blisters and erythema on fingers
1971	USA. Chemist exposed two fingers because he did not realize his hand was in an unfiltered beam of x rays from a diffraction apparatus [V2]	Not quoted	Swelling and stiffness of knuckles

Table 56, continued

Year	Description of accident	Dose/activity	Clinical effects
1973	USA. Chemist looked directly into primary beam from a diffractometer while aligning the beam [V2]	Not quoted	Burns to eyes
1974	USA. Technician in a geological survey laboratory held an energized fluoroscopic tube near to his chest while testing for a vacuum leak [V2]	Not quoted	Severe erythema of chest
1974	USA. Radiochemist placed hands near the beam port of a spectrometer not realizing it was on [V2, U12]	Dose to hand 24-48 Gy	Some loss of tissue and function to left index finger and injuries to several other fingers and right thumb
1975	USA. Chemist exposed to x rays when the shutter on a diffractomer failed [V2]	Not quoted	Burns on index and middle finger
1976	USA. Research worker inadvertently moved lead shielding plate while aligning the beam of a diffractomer [V2]	Not quoted	Burns on palm of hand
1977	USA. Research worker exposed hands while changing samples in a diffractometer because safety cut-off system had defective wiring [V2]	Not quoted	Burns and swollen hands
1978	Switzerland. Physicist handled a silver source which had been irradiated in a research reactor [P8]	Dose to fingers 20-100 Gy Total body dose 0.007 Gy	Second degree burns on fingers
1978	USA. Worker exposed near view port of a linear accelerator while attempting to cure a problem with insulation [V2]	Not quoted	Blistering on lips, back of hands and reddening of thighs and stomach

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