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SOURCES AND EFFECTS OF IONIZING RADIATION

United Nations Scientific Committee
on the Effects of Atomic Radiation

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ANNEX E

Doses from occupational exposure

CONTENTS

Introduction

1. In its 1962 report (116), the Committee discussed the contribution made to the population dose by occupational exposure. At that time it was concluded that the annual genetically significant dose (GSD) from this source was unlikely to exceed a value of 0.5 mrad. The subject was considered again in the 1972 report of the Committee (117), and it was noted that the annual GSD had been estimated in two countries as 0.07 mrad, with a corresponding *per caput* dose of about twice this value. Other estimates of the annual *per caput* dose ranged from 0.01 to 0.8 mrad. Both reports presented information on the number of workers in various countries which appeared to remain constant at about one or two per thousand of total population.

2. The 1972 report, in particular, presented a considerable body of data which showed that the majority of radiation workers (or the majority of those monitored) receive very low exposures. The occupational collective dose due to the production of electricity by nuclear power was estimated in 1972 as about 2-3 man rad per MW y; most of this dose was thought to have been incurred during the reprocessing of nuclear fuel. It was anticipated that improved technology would result in lower collective doses per unit of electrical energy produced. Doses over the recommended limits and injuries were found to be extremely rare in most kinds of radiation work with a few notable exceptions (e.g. industrial radiography, x-ray crystallography, mining and luminizing).

3. The purpose of this Annex to the current report is to provide some data to enable the conclusions of the two previous reports to be verified or modified if necessary. The main objectives are twofold, however. First, it is the intention of the Committee to examine particular occupations, and even particular job categories within occupational groups, which consistently give rise to the highest average doses and high collective doses. It is hoped in this way to identify the areas towards which a greater proportion of the available effort should be directed to reduce the levels of occupational doses; as a corollary to this, data on selected groups of individuals have been examined in an attempt to predict the likely values of lifetime doses to which occupationally exposed workers may be subjected.

4. In view of the burgeoning nuclear power industry, the second main objective is to concentrate on trying to obtain an overall view of the individual and collective doses associated with each operation in the nuclear fuel cycle. In particular, any trend of doses with time is of interest to see whether the prediction of a gradual decrease in collective dose per unit of electrical energy produced that was made in the 1972 report is being fulfilled.

I. BASIC INFORMATION

A. SOURCES OF DATA

5. It was noted in the 1972 report that much of the data supplied to the Committee was unpublished. In the intervening period, some data have been published, but these have tended to be mainly from countries with large or growing nuclear power programmes and have not filled in many of the gaps in the data available in 1972.

B. LIMITATIONS OF THE DATA

6. Most of the limitations of the data were identified in the 1972 report, but for the sake of completeness they are briefly summarized here again. Data on occupational exposure are generally obtained from personnel-monitoring programmes set up to satisfy legal or operational requirements. These data are not always suitable for interpretation as dose estimates in the form required by the Committee.

7. Accurate assessment of dose at the lower exposure levels is severely limited by a number of factors. The proportion of workers issued personal monitoring devices varies greatly from place to place. In some establishments virtually all staff are routinely issued individual monitoring devices, while in others only those workers whose exposures might exceed 0.3 of the annual dose limit are so monitored (51).

8. Another practical difficulty is the recording of doses which fall below the minimum detectable level of the monitoring device. These may be recorded either as the minimum detectable level or as zero. Since records usually do not indicate the procedures used for deriving the doses, it is not, in general, possible to correct for any instrumental or natural radiation background which may have been included. Because of these problems and in view of the large number of doses falling in this category, the collective dose contribution from the lowest dose interval is often not well known. The Committee has therefore used an analytical procedure based on the distribution of doses at higher levels to extract mathematically the average dose and the proportion of the collective dose above and below a certain datum. This method is described in chapter III.

9. The problem of the relationship between the response of the personal monitoring device and the dose received by the person wearing it was discussed in depth in the 1972 report. It is almost always the reading from the dosimetric device which is reported, without consideration of the relationship between this reading and the whole-body or organ dose actually received by the wearer. Since most of the data relate to external whole-body exposure to directly ionizing radiation, the Committee, while recognizing the problem, has decided once again to adopt a convention that all numerical results reported by monitoring services represent the average whole-body absorbed dose in tissue. In view of the lack of available information on calibration and analysis procedures from personnel dosimetry services, the Committee was unable to apply any more rigorous procedure. Other results, such as those in which specific organ doses are reported or where a substantial proportion of the dose is due to high-LET radiation, are treated as special cases.

10. It is likely that the direct use of data from personnel-monitoring programmes in this way will tend

to overestimate doses in the various tissues of interest. For example, even in the case of the exposure of radiologists to x rays during fluoroscopy, the results of an investigation (56) in Poland showed that the film badge gave a reasonable estimate of the surface dose to the trunk but an overestimate of the gonad dose. High doses to the extremities did, however, result in the chest film badge underestimating the average whole-body surface dose by a factor of two. In many cases, such extremity doses are separately monitored and reported.

11. It is even more difficult to group and compare the results of personal monitoring for internal exposure. In some cases, routine monitoring of individuals is carried out, e.g., tritium-in-urine monitoring of luminizers and monitoring of plutonium incorporation in nuclear-fuel processing workers by various techniques. In other cases, surveys of the working environment together with relatively small numbers of individual measurements are used to deduce doses, as in the case of lung doses received by uranium and other miners. In most other work places, the ambient levels of radioactivity are usually maintained at low levels, and therefore significant internal exposures of workers seldom occur. In these situations, internal monitoring procedures tend to be carried out as a consequence of incidents or as part of an experimental study, rather than as a routine practice.

II. REASONS FOR PRESENTING OCCUPATIONAL DOSE STATISTICS

12. The primary purpose for which almost all of the data on occupational doses presented here were collected was to demonstrate compliance with statutory or regulatory obligations regarding doses to individuals. The data are therefore in general not reported in a form which lends itself to further interpretation. The Committee wishes to emphasise that data collection and reporting in excess of these obligations must be justified and therefore sets out in this section the reasons for so doing. Given these reasons, the Committee recommends that, where possible, further uses of data reported should be borne in mind by the compiler so that the format and quantity of data can be made more suitable for these purposes.

13. The purposes of such further data compilation and analysis may be source justification, relative cost-benefit assessment, evaluation of trends, and indication of the worker's risk level. Each of these purposes is examined in turn.

A. SOURCE JUSTIFICATION

14. In order to judge the justification of practices which cause radiation exposures, the levels of individual doses and the collective dose or collective dose commitment are relevant quantities in respect of presumed radiation detriment. The detriment indicated by the collective occupational dose should be added to any other detriment caused by the practice. It is often convenient to express the collective dose relative to a unit of practice. This unit of practice should be chosen to represent the benefit from the practice and not something which may well represent the size of the practice but have no close correlation to its benefit. For example, the number of workers may be proportional to the magnitude of a practice, but is not necessarily a measure of results. For this reason the average dose, i.e., the collective dose divided by the number of workers, is often not useful in considerations of justification.

15. In some circumstances it may also be relevant to compare the collective dose to occupationally exposed workers and the collective dose to the general public or to recipients of the practice. This may be the case when evaluating the detriment from discharges of radioactive effluents from waste treatment plants or in some medical situations. In general, these two situations are characterized by quite different relationships between occupational and public doses. Effluent discharges, particularly from reactors and other nuclear establishments, generally give rise to public collective doses that are almost insignificant compared with the collective doses to the plant personnel.

B. RELATIVE COST-BENEFIT ASSESSMENT

16. The purpose of relative cost-benefit assessment is to explore whether it is reasonable to attempt to achieve a further reduction of radiation doses from a practice which has been found justifiable even at existing dose levels. It is therefore the mechanism for finding the dose level at which the overall cost of further dose reduction is equal to the cost of the presumed detriment which would be eliminated by the dose reduction.

17. For this purpose the collective dose is the relevant quantity in so far as it can be assumed to represent the radiation detriment (see Annex A). It may not be sufficient, however, to give information only on the total collective dose or collective dose per unit practice. It would often be helpful to have additional information on particular sources of substantial fractions of the collective dose. This may help to direct attention to particular practices or jobs for which alternatives can be sought.

18. One way of obtaining information on available means of dose reduction is to compare the dose levels at which the same practice is carried out in different establishments or in different countries. For this purpose the collective dose per unit practice would suffice to give the crude primary comparison and is better for this purpose than the average dose.

C. EVALUATION OF TRENDS

19. There are at least two reasons for following trends in occupational doses. One is to be aware of changes in the total radiation burden from a given practice. The most direct measure of the radiation burden from

occupational doses associated with a given practice is the collective dose, so this should be continually reassessed as a function of time to detect overall trends. The collective dose at any time will not necessarily be simply related to the size of the practice because changes in radiation protection techniques are likely and the methods employed in the practice will be affected by the size of the practice.

20. The other reason for assessing trends is to determine whether radiation protection efficiency is being maintained at acceptable levels. Any quantity used for this purpose must be handled with caution. The total collective dose will reflect both the protection efficiency and the magnitude of the practice. The collective dose per unit practice will react to changes in the practice efficiency as well as the protection efficiency. The average dose is dependent on the number of people considered. For these reasons any deductions from apparent trends should be based not only on the *prima facie* evidence but also where possible on an investigation of the underlying reason for the trend.

D. INDICATION OF THE LEVEL OF RISK IN PARTICULAR OCCUPATIONS

21. It is difficult to describe precisely in advance the risk situation of an individual worker before his doses over a reasonable period have been measured or assessed. Once the doses he has received are known, however, his individual risk of harmful effects could, in principle, be assessed. The following two types of information are of use in assessing the risk situation in different occupations: *(a)* the general level of risk in a particular occupation; *(b)* the identification of sub-groups with a higher level of risk than the average for that occupation or for work in general.

22. In order to assess the general level of risk it is necessary to relate this to some measure of the dose distribution. If the average annual probability of inducing harm in a working population of N persons in a particular occupation is P_H, the expectation of harmed persons is $P_H N$.

23. Conceptually, P_H is obtained from the product of the probability of receiving a dose between D and $D + dD$, which could be called $P(D)dD$, and the probability of harm given the dose D which could be called $P(H \mid D)$. Therefore

$$P_H = \int_0^\infty P(D)\, P(H \mid D)\, dD$$

If we further assume, given the discussion in Annex A, that the risk of harm at a given dose D is proportional to D, the above expression becomes

$$P_H = k \int_0^\infty P(D)\, D\, dD = k\bar{D}$$

which shows that the average dose is the proper quantity to indicate the general level of risk in a particular occupation, given the assumption of proportionality between dose and risk of harm. It is also the proper quantity to determine an individual's *a priori* risk.

24. In practice, doses are monitored and information on the dose distribution for the occupation will be available. The distribution may include doses approaching or exceeding the recommended maximum permissible doses. These high doses may be delivered to different individuals each year or to the same individuals year after year. In the second case these individuals will be in a higher risk class than the average for the occupation as a whole. It is therefore of interest to identify such subgroups. It may also be of interest to detect an occupation giving rise to high doses even if these are to different individuals each year, since the doses may still be due to causes which might be eliminated. The mathematical formulation of the portion of the distribution defined as including high doses is developed in the next chapter.

III. ANALYSIS OF DOSE DISTRIBUTIONS

25. In the 1972 report of the Committee it was noted that surprisingly little information had been published on occupational exposure in the scientific literature, although there was a considerable body of data in sources of limited availability, such as annual reports. That body of data is steadily growing, but, in addition to being of limited availability, it consists of information that is not presented in a standardized form. This makes intercomparison difficult, and compilations of data tend to be rather complex and unclear.

A. THE LOG-NORMAL DISTRIBUTION

26. On the basis of preliminary results in analysing data on occupational exposure, there is reason to expect that individual doses would follow a log-normal distribution. It is usually difficult to verify that they do, since doses tend to be grouped within wide bands and the lowest band includes non-exposed persons. However, detailed analysis of personal film dosimeters from a thousand persons working in diagnostic radiology has been carried out by Bäuml *et al.* (11) in the Federal Republic of Germany. Taking advantage of the increased film sensitivity for low-energy x rays, annual doses as low as 12 mrad were estimated with sufficient precision. The results of this analysis plotted as a log-probability curve are shown as curve A in figure I; it approximates a straight line, indicating that the actual dose distribution is well fitted by a log-normal distribution.

27. The data given by Bäuml *et al.* are very detailed. However, most of the data received by the Committee are given in only three or four ranges of dose. Curve B in figure I is plotted using the data from Bäuml *et al.* for annual doses in the ranges 0-0.5, 0-1.5, and 0-5 rad. The geometric mean doses read from these curves are 12 mrad (curve A) and 20 mrad (curve B). The proportion of people receiving less than 10 mrad (unirradiated) is estimated as 46 per cent from curve A and 36 per cent from curve B. Therefore, it appears that data from only a few dose ranges can be used for estimating the geometric mean dose and frequency of low doses with a reasonable degree of accuracy and also for assessing the average dose by means of the relationship given in

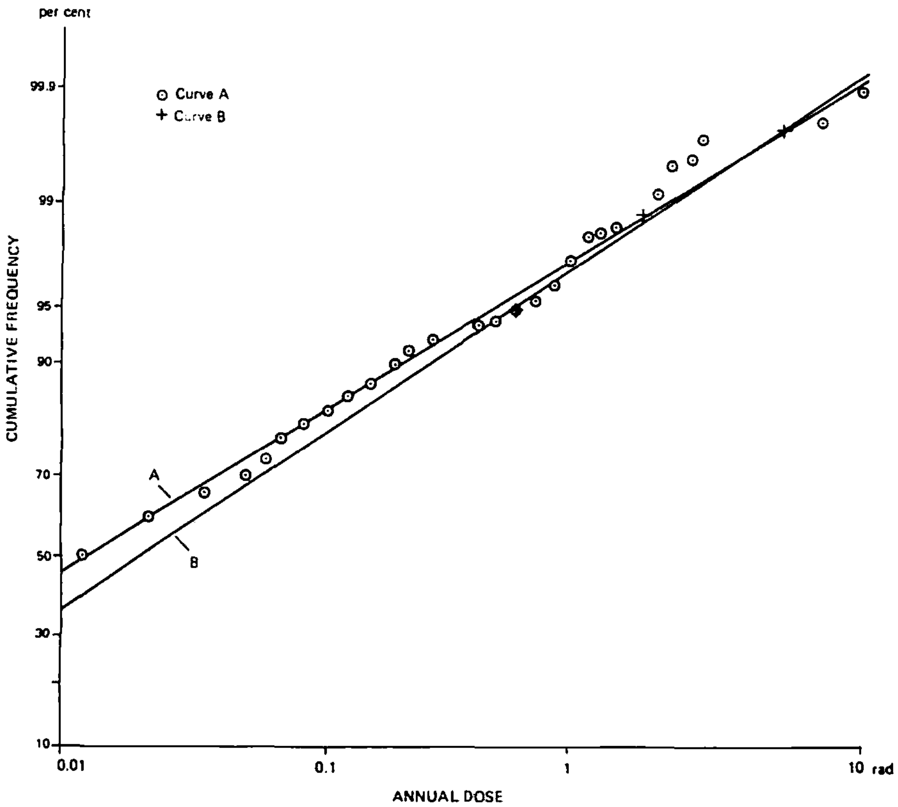

Figure I. Log-probability plot of annual doses to diagnostic x-ray workers in the Federal Republic of Germany

section C of this chapter. For example, the average dose $\bar{D}$ is estimated to be 120 mrad from curve A and 130 mrad from curve B.

28. Brodsky (16) has analysed a number of samples of dose distributions from occupations in medicine and industry and found that, in general, they followed a log-normal distribution. All distributions observed were of this form up to a level of about 1 rad, and for some it was true into the higher region. The deviation from log-normal above 1 rad, showing that fewer people were exposed to high doses than would be expected, was attributed to the effect of occupational exposure limits and was particularly noticeable for distributions with annual doses exceeding 5 rad. Examples of this deviation are shown in figures IX and X (para. 75).

29. On the basis of this evidence and after examining many of the actual dose distributions for different occupations used in later sections of this report, the Committee has decided to make the assumption that annual dose distributions are log-normal, except possibly for annual doses approaching or exceeding 5 rad. This assumption enables different types of data tabulation to be treated consistently in order to extract parameters which can be compared with those of the reference distribution to be discussed next.

B. THE REFERENCE DISTRIBUTION

30. In order to characterize those aspects of a dose distribution which contain relevant information for the objectives outlined in chapter II, it is helpful to define a reference distribution with the following clear properties:

(a) The distribution of annual doses is log-normal;

(b) The mean of the annual dose distribution is 0.5 rad (one tenth of the ICRP maximum permissible annual whole-body dose);

(c) The proportion of workers exceeding the maximum permissible annual dose of 5 rad is 0.1 per cent.

It appears to the Committee that a distribution with these properties would comply well with the intent of the ICRP dose limitation system for persons exposed to radiation in the course of their work. The mathematical construction of this reference distribution is described in appendix I. Some important parameters of the reference distribution which follow from the above definition are given below:

Annual dose range (rad)	*Probability of an annual dose in the range*	*Fraction of the total collective dose contributed by doses in the range*
0-0.5	0.668	0.253
0-1.5	0.956	0.690
0-5.0	0.999	0.941

31. In order to compare dose distributions with each other and the reference distribution, some comparison parameters must be identified. These should be related to the requirements of chapter II. The collective dose has already been recognized as useful for some purposes, but it is not a function of the dose distribution and is not considered further here. The average dose (arithmetic mean) is another relevant parameter, and, as already pointed out, the analysis of the data as log-normal should permit more consistent estimates of

the average dose. It is therefore considered to be a fundamental parameter of the distribution. The problems of defining the tail of a distribution were mentioned in chapter II. One possibility would be to use the relative numbers of persons receiving high doses; this, however, would give no information on the magnitude of the high doses. Another possibility would be to use the average dose for those individuals who receive doses above a certain level; this has the disadvantage that a few persons receiving high doses would carry too much statistical weight. It would therefore seem better to combine the two approaches and use the fraction of the collective dose in the high-dose tail. The annual dose level above which the tail is defined is obviously a somewhat arbitrary choice, but 1.5 rad seems a reasonable choice as it is the dose above which ICRP recommends special attention and is often used administratively as a dividing level in reporting readings. This measure is therefore defined as the fraction of the collective dose due to annual doses above 1.5 rad, i.e. $S_{1.5}/S$, and for the reference distribution it is $1 - 0.690 = 0.310$ (see table in paragraph 30 above). In order to normalize, we define a dimensionless quantity, Ω, as the ratio of the fraction of the collective dose due to annual doses above 1.5 rad for the observed distribution to the fraction for the reference distribution. For any observed distribution, therefore,

$$\Omega = (S_{1.5}/S)/0.310 = 3.23\, S_{1.5}/S$$

32. For the reasons referred to in chapter I, many persons who are issued a personal monitoring device will receive essentially no incremental dose due to their work. The number of such persons will be determined only by the policy of issuing dosimetric devices. In order to make a more realistic estimate of the collective dose associated with any given practice, it would be useful to be able either to calculate the average dose to those persons actually exposed, together with an estimate of their number, or to have a method of extracting the collective dose which is not sensitive to the number of essentially unirradiated people included in the sample. A further advantage of the use of a log-normal distribution analysis technique is that it enables the average dose to be calculated from the entire distribution without attaching too much importance to the lowest dose interval. It could be thought necessary to draw a distinction between this average dose calculated assuming the dose distribution to be log-normal (α) and the average dose obtained by dividing the total collective dose by the total number of individuals included in the distribution ($\bar{D}$). For distributions which are exactly log-normal, α and $\bar{D}$ will be the same and, in practical cases, as shown below, the difference is too small for the distinction to be worth making.

33. The effect of the addition or subtraction of large numbers of unirradiated individuals may be seen from the following example, which uses the data for United States agreement state licensees reported by Klement *et al.* (64). These data were chosen because they are an example of a set of data for which the annual dose distribution is available down to 0.1 rad. The procedure adopted was arbitrarily to add to, and then subtract from, the number in the lower annual dose range (0-0.1 rad), assuming 10 000 workers to have been unirradiated. This is a significant number compared with the 17 041 workers in this range in the original distribution and the original total of 24 519 workers. The resulting log-probability plots are shown in figure II, where curve A represents the original data, curve B shows the result of adding 10 000 workers in the 0-0.1 rad range, and curve C shows the result of subtracting 10 000 workers from the original number in this range.

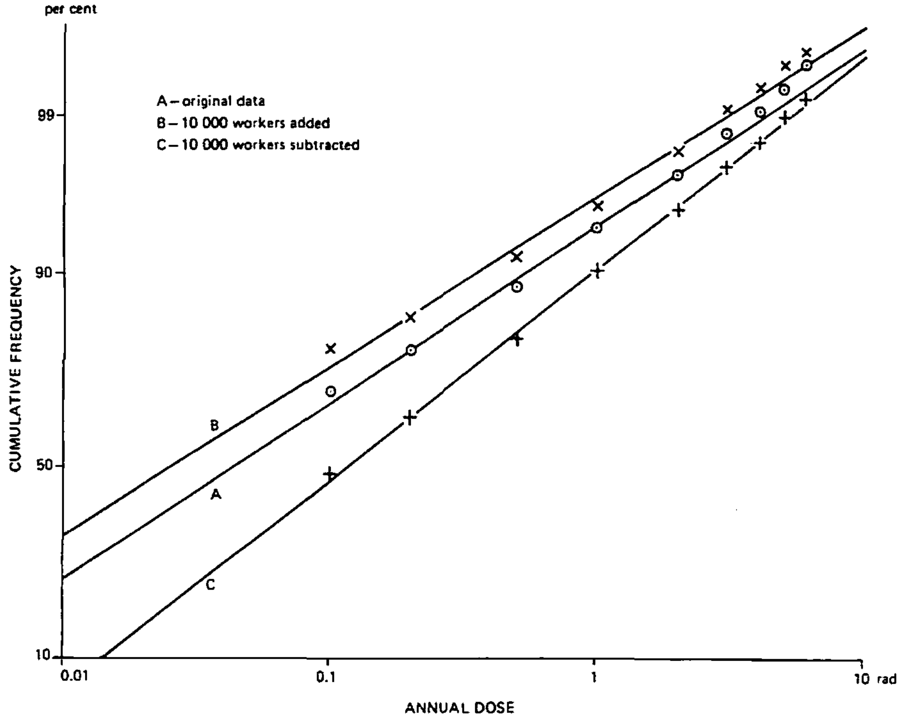

Figure II. Log-probability plot of annual doses to United States agreement state licensees, with addition and subtraction of 10 000 workers in the lowest dose range

34. Several observations can be made about these curves. The fit to a log-normal distribution is reasonably good for all three curves, indicating that arbitrary administrative decisions on issuing dosimeters do not greatly affect the conclusions. The collective doses calculated from the two extreme curves are 6890 and 6350 man rad for curves B and C, compared with 6660 man rad from curve A. The average annual doses calculated from the log-normal plot (α) are 0.1996 and 0.4371 rad for curves B and C, compared with 0.2718 rad from curve A (shown to four decimal places for comparison), demonstrating the dependence of this parameter on the number of workers considered. For comparison, the average annual doses calculated by dividing the collective dose by the number of workers ($\bar{D}$) are 0.1996 and 0.4374 rad for curves B and C and 0.2716 rad from curve A. For all practical purposes, α and $\bar{D}$ are therefore the same.

35. In order rapidly to compare dose distributions without the need to evaluate masses of raw data, it is sufficient therefore to extract from the distributions the collective dose S, the average dose $\bar{D}$ and the ratio Ω. It may also be of use to have the variation of these quantities with time. The collective dose S should be related to the benefit derived from the practice giving rise to the doses–it is not directly useful in itself. The average dose $\bar{D}$ represents the average level of risk in a given occupation or subgroup; in comparison with the reference distribution, occupations with high values of $\bar{D}$ would merit special attention. Similarly, occupations with high values of Ω should receive closer study. Occupations for which $\bar{D}$ or Ω are relatively small are probably those in which very little personnel monitoring need be carried out to meet the requirements of individual protection (see also chapter VII).

C. EXTRACTION OF THE PARAMETERS OF A DISTRIBUTION

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

$$dp = P(y)\,dy = \frac{1}{\sigma\sqrt{2\pi}}\, e^{-\frac{(y-\mu)^2}{2\sigma^2}}\, dy$$

The probability of a value of x lying between x and $x + dx$ is therefore

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

The arithmetic mean of the distribution of x is given by

$$\alpha = \int_0^\infty x P(x)\,dx = e^{\mu+\frac{\sigma^2}{2}}$$

Therefore, a simplified form of "probit analysis" can be used to assess the parameters of the distribution. A probit is a transformation which, when applied to the variate, will transform it to a straight line. A probit value is assigned to each probability value so that a plot of probit versus the logarithm of dose will also give a straight line. Some parameters can be readily estimated using a line fitted to the distribution by the method of least squares. The median, which is at a cumulative frequency of 50 per cent, is e^{μ}. In addition, the value of $y(= \ln x)$ is $\mu - \sigma$ at a cumulative frequency of 15.87 per cent and $\mu + \sigma$ at a cumulative frequency of 84.13 per cent. This procedure therefore enables μ, σ and α to be determined simply.

37. In some cases, a procedure was used which involved fitting a log-normal function to the data up to an annual dose value determined by inspection and using actual data points above this value. This procedure was used, for example, in analysing the dose distribution shown in figure VIII. A similar procedure, but with a different upper limit for the log-normal fit, was used for the dose distribution shown in figure X. In the few cases where the data did not fit a log-normal distribution sufficiently well to justify curve fitting, the values of the parameters for comparison with the reference distribution were obtained directly from the dose distribution, using the mid-point doses in the various dose ranges mutliplied by the number of workers in the range to obtain the collective dose.

IV. NUMBER OF WORKERS EXPOSED TO RADIATION

38. In 1966, the ICRP introduced (51) the concept of a single category of occupational exposure, namely the radiation exposure of any worker in the course of his work. The accompanying recommendation by the ICRP, that two conditions under which workers are exposed could be considered for administrative purposes, seems not to have been fully realized in practice. Under this recommendation, only people working in conditions such that their resulting doses might exceed 0.3 the annual maximum permissible dose require individual personal monitoring and health supervision. The expected result of this recommendation was that a considerable number of workers, employed under conditions such that their exposures were most unlikely to exceed 0.3 the annual maximum permissible doses, would no longer be subject to personal monitoring, but, as far as can be ascertained, no such change has occurred. The vast majority of persons routinely issued with personal monitoring devices still record annual doses less than 0.3 the maximum permissible doses.

39. Most of the data received relates to those persons potentially exposed to radiation who have been issued with individual monitoring devices or whose environment has been sufficiently closely monitored that good estimates of individual exposures can be made. There are in addition substantial numbers of people potentially or actually exposed to radiation who are not monitored in these ways and whose doses can only be inferred by modelling techniques similar to those used to estimate the doses to members of the public.

40. In practice, it is difficult to identify all occupational exposures. It is generally agreed that the term applies both to workers actually handling radioactive materials or radiation generators and to those employed on the same site (by the same or other employer) who may be exposed to radiation only

because of their physical presence there, e.g., typists and bricklayers. Less obvious is the situation of an employee of a different organization who, as a result of proximity or through discharge of wastes, is irradiated at his work. His doses, even if monitored, may not always be reported anywhere as "occupational". Since in principle any use of radiation gives rise to a very wide distribution of very small doses, it seems reasonable in practice to ignore doses that are sufficiently small. If protection of people directly connected with the radiation or on the same site is to be ensured, then doses to people unconnected with the work will generally be negligible from the point of view of individual risk. It would therefore seem more reasonable to include these people with the general public in assessing their levels of protection and the effects of doses to them. This would also avoid the anomalous situation of a man working in an office at home being permitted an annual dose of 1.5 rad, while his wife in the next room would only be permitted 0.5 rad, even through they are exposed to the same (extraneous) source.

41. Since the Committee had expressed an interest in doses to particular subgroups of workers in larger occupational groups,· a number of countries have submitted information on the type of work and the category of worker as well as the overall statistics. In order to overcome the objections above to defining workers involved with radiation in a general way, one alternative would be to attempt to define subgroups of workers and types of work in such a way that the dose distribution of each subgroup is relatively well characterized and the subgroups are mutually exclusive. Then by combining the subgroups it would be possible to survey any given category of worker. For such a system to work, considerably more thought will have to be given to defining the categories than has been given in those systems of which the Committee has knowledge.

42. In the 1972 report, data derived from personnel-monitoring programmes were used to estimate the number of persons exposed to radiation in the course of their work. For comparison, similar data (1, 19, 38, 44, 49, 64, 97, 98, 122) are presented in table 1. In many cases the figures are from the same sources as those represented in the 1972 report. Country totals are given only if it appears that the estimates are reasonably comprehensive. Although these may be of interest, they are not used as such for any of the purposes of chapter II.

V. OCCUPATIONAL EXPOSURE IN THE NUCLEAR FUEL CYCLE

43. As shown in the 1972 report, occupational exposure accounts for a substantial part of the collective dose due to the nuclear fuel cycle. It is therefore important to assess, in addition to the individual doses, the collective dose associated with each operation of the fuel cycle and, where possible, to relate, for each operation, the collective doses to the production of electrical energy. It is also of interest to analyse the temporal trend of the doses and, in particular, to see if the collective dose per unit electrical energy generated has decreased, as was thought likely in the 1972 report.

44. In this chapter, the most recent information on the distribution of doses in different dose ranges is used to obtain the parameters defined in chapter III. Where the data can be fitted by a log-normal distribution, the parameters are calculated on the basis of a least-squares fit. In those cases where there are insufficient data or for some reason the fit deviates significantly from log-normal, the parameters can often still be estimated by direct calculation from the raw data. This is done where possible. In order to clarify the interpretation of the data, the information as supplied to the Committee is presented in tabular form in appendix II (tables 46-96), and ordinarily only summaries or the extracted parameters are given in this Annex. The various stages of the nuclear fuel cycle are discussed in turn.

A. URANIUM MINING

45. One of the main radiological protection problems highlighted during the 1960s and early 1970s was the exposure of underground mine workers to high concentrations of radon and its daughter products. It was noted in the 1972 report that during the previous years there had been a marked improvement in working conditions in mines, with a subsequent lowering of the exposure to radon and its daughter products. French data (54) indicate that this improvement has continued. A discussion of the relationship between radon daughter exposure and dose to respiratory tissue can be found in Annex B (paras. 152-209). Measurements of radon concentrations in a Yugoslav mine (68) range form 90 pCi l^{-1} in the tunnels to 800 pCi l^{-1} in stopes with bad ventilation. The mean concentration of radon in French mines is only 130 pCi l^{-1}, because of greatly improved ventilation systems.

46. In South African gold-and-uranium mines, radon daughter concentrations in excess of 1 WL (see Annex B for definitions and discussion of the units WL and WLM) are found in places where uranium is the major mineral and gold is of secondary importance (36). An average of 0.9 WL was recorded for the uranium section of one such mine (9). The average of the annual reported exposures to radon daughters in 1974 in underground mines in the United States is 1.4 WLM (34). Table 46 (appendix II) shows the results of monitoring of French underground mines for exposure to radon daughters (54). It can be seen that the average exposure level had decreased from about 0.18 WL in the period 1971-1973 to 0.11 WL in 1975, by which time the proportion of workers exposed to 0.3 WL had dropped from 22 per cent to nearly 5 per cent.

47. Some information is available on the external gamma irradiation in uranium mines (68, 91, 93). In French uranium mines (91) the dose rates are of the order of 0.5 mrad h^{-1} in the centres of galleries where the ore is of low concentration, but can reach 100 mrad h^{-1} in the few places where the ore concentration is exceptionally rich. Dose rates in Yugoslav mines (68) can be up to 5 mrad h^{-1} near the ore. The average annual external dose to a small group of underground uranium miners in Japan is 122 mrad (41). The average of many measurements of dose rates in underground mines in the United States is 1.3 mrad h^{-1}

TABLE 1. NUMBER OF OCCUPATIONALLY EXPOSED PERSONS AND THEIR PROPORTION IN THE POPULATION OF VARIOUS COUNTRIES

Data derived from personnel monitoring records

(Absolute number n *and number per 1000 of population* (10^{-3})*)*

Country	*Type of occupation*														Year	*Total*		
	Extractive industries		*Atomic industries*		*Non-atomic industries*		*Medical*		*Research and education*		*Other*		*Armed forces*			*Best estimates*		*From 1972 report*
	n	(10^{-3})	n	(10^{-3})	n	(10^{-3})	n	(10^{-3})	n	(10^{-3})	n	(10^{-3})	n	(10^{-3})		n	(10^{-3})	$(10^{-3})^a$
Argentina	150	<0.01	1 300	0.05	220	0.01	9 850	0.42	29	<0.01	40	<0.01			1971	11 000	0.5	0.1
Australia			1 007	0.08	1 782	0.14	12 219	0.96	3 233	0.25	420	0.03			1971	19 000	1.5	1.5
Austria	170	0.02			800	0.11	1 800	0.24							1971	3 000	0.4	
Barbados							40	0.17							1971	100	0.2	
Belgium			2 140		2 485		4 656		6 100							15 000		
Burma					15	<0.01	165	<0.01	5	<0.01	4	<0.01			1971	200	<0.01	
Canada			2 000	0.01	——	——	——	—— 31 000	1.45 ——	——	——	——			1971	33 000	1.5	
China			60	<0.01	10	<0.01	700	<0.01	500	<0.01	100	<0.01			1971			
Colombia			100	<0.01	37	<0.01	12 000	0.57							1971	12 000	0.6	
Cyprus					4	0.01	65[a]	0.01	4	0.01					1971			
Democratic Kampuchea							240	0.04							1971	300	<0.1	
Denmark					406	0.08	4 808	0.96	2 067	0.41					1973	7 000	1.5	1.9
Finland			5	<0.01	350	0.07	4 700	1.00	40	0.01	400	0.09			1971	6 000	1.2	0.9
France			15 000	0.30	15 000	0.30	60 000	1.20	10 000	0.20					1975	100 000	2.0	2.1
German Democratic Republic															1972	34 000	2.0	1.5
Germany, Fed. Rep. of							87 056	3.35	——	—— 24 069	0.93 ——	——			1975	111 000	4.3	
Ghana					46	0.01	196	0.02	32	<0.01	1	<0.01			1971	300	<0.1	
Greece	10	<0.01			40	<0.01	2 500	0.28	500	0.06					1971	3 000	0.3	
Guyana							46	0.06							1971	100	0.1	
Hungary					1 647	0.16	5 183	0.50	126	0.01	334	0.03			1971	7 000	0.7	
Iceland					15	0.07	400	1.90	15	0.07					1971	400	2.0	
India	2 561	<0.01	7 887	0.01	2 580	<0.01	10 913	0.02	2 450	<0.01					1971	26 000	0.5	
			5 578	–	1 760	–	7 739	–	1 562	–					1973	16 000		
Indonesia	92	<0.01	100	<0.01					18	<0.01	9	<0.01			1971			
Iraq							450	0.05	250	0.03	90	0.01			1971	1 000	0.1	
			267	0.03	6	<0.01	624	0.07							1972	1 000	0.1	
Ireland	4	<0.01			45	0.02	580	0.20	55	0.02					1971	700	0.2	
Israel			907	0.30	231	0.08	2 794	0.94	646	0.22					1971	4 500	1.5	
Italy			4 600	0.09	2 300	0.04	18 000	0.34	120	<0.01	800	0.01			1971	26 000	0.5	0.7
Jamaica							62	0.03	2	<0.01					1971	100	<0.1	
Luxembourg					255	0.75	265	0.78							1971	600	1.5	

TABLE 1 *(continued)*

	Type of occupation															*Total*		
	Extractive industries		*Atomic industries*		*Non-atomic industries*		*Medical*		*Research and education*		*Other*		*Armed forces*			*Best estimates*		*From 1972 report*
Country	n	*(10⁻³)*	n	*(10⁻³)*	n	*(10⁻³)*	n	*(10⁻³)*	n	*(10⁻³)*	n	*(10⁻³)*	n	*(10⁻³)*	*Year*	n	*(10⁻³)*	*(10⁻³)*[a]
Madagascar							215	0.03			5	<0.01			1971	300	<0.1	
Malawi							23	0.01							1971	100	<0.1	
Malaysia							460	0.04			40	0.01			1971	500	<0.1	
Mali							26	0.01							1971	100	<0.1	
Malta							<100	<0.31							1971	100	<0.3	
Mauritius							73	0.09							1971	100	0.1	
Mexico	148	<0.01	56	<0.01	271	0.01	488	0.01	93	<0.01	33	<0.01			1971	1 000	<0.1	
New Zealand					137	0.05	2 735	0.97	300	0.11	364	0.13			1971	4 000	1.3	1.3
Netherlands			260	0.02	1 100	0.08	9 000	0.69							1971	10 000	0.8	0.8
Nigeria	>5 000	>0.08			2 000	0.03	4 000	0.06	200	<0.01					1971	11 000	>0.2	
Norway			598	0.15	326	0.08	7 460	1.92			15	<0.01			1971	8 000	2.2	2.7
Peru															1971	8 000	0.6	
Philippines	6	<0.01	180	<0.01	164	< 0.01	405	0.01	6	<0.01	11	<0.01			1971	800	<0.1	
Poland			1 253	0.04			1 298	0.04			2 786	0.09			1971			
						14 600	0.45								1971	20 000	0.6	0.5
Rwanda	2	<0.01			52	0.01	2	<0.01							1971	100	<0.1	
Sierra Leone	<20	<0.01					<100	<0.04							1971	100	<0.1	
Singapore					40	0.02	85	0.04	35	0.02					1971	200	0.1	
Socialist Rep. of Viet Nam					100	<0.01	439[b]	0.01	20	<0.01	3	<0.01			1971	600	<0.1	
Spain	500	0.02	2 300	0.07	100	<0.01	200	0.01	300	0.01					1971	4 000	0.1	
Sudan					26	<0.01	196	0.01	50	<0.01					1971	300	<0.1	
Sweden	5 136	0.64	1 188	0.15	1 000	0.12	12 000	1.49	1 300	0.16					1971	21 000	2.6	2.0
Switzerland															1974	15 000	2.4	
Thailand							878	0.03	90	<0.01	12	<0.01			1971	1 000	<0.1	<0.1
Tunisia							100	0.02			6	<0.01			1971	100	<0.1	
Turkey	65	0.02			60	0.02	2 000	0.56	250	0.07	70	0.02			1971	2 500	0.7	
United Kingdom			19 700	0.36	22 250	0.40	24 200	0.44	12 000	0.22					1974	78 000	1.4	
			22 787	0.41							2 798	0.05			1971			
United States			125 000[b]	0.61	90 000[b]	0.44	453 700	2.21	23 000[b]	0.12			80 087	0.39	1970	772 000	3.8	3.7
Venezuela	25	<0.01	40	<0.01	121	0.01	3 200	0.31	410	0.04	8	<0.01			1971	4 000	0.4	
Zambia	30	0.01			5	<0.01	250	0.06	15	<0.01					1971	300	0.1	

[a] Government establishments only.

[b] Estimated number of workers in these groups.

(93). Since a miner in a tunnel is exposed to something between a plane (2π) and a completely surrounding (4π) source, the conversion procedures given in Annex A for the assessment of tissue doses in a 3π geometry can be used. On this basis, and assuming 2000 h of work per year and a dose rate of 1.3 mrad h^{-1}, the annual average absorbed dose (in the gonads or bone marrow) is estimated to be 1.6 rad. However, as shown in table 47 (appendix II), measurements of the external doses to French underground miners show a decrease in the annual average dose from about 1 rad in the period 1971-1972 to 0.5 rad in 1975. It therefore seems reasonable to assume an annual average dose of 1 rad for current conditions in uranium mines throughout the world.

48. The assessment of the collective dose per unit electricity for the mining operation requires an estimation of the number of miners involved in the extraction of the amount of ore needed to produce 1 MW y of electrical energy. Assuming that one miner produces 3 t of U_3O_8 in one year and that 160 t of U_3O_8 are required to fuel one 1000-MW(e) light-water reactor for a year (114), it is estimated that the fraction of a man year required to produce 1 MW y of electrical energy is $5.3\ 10^{-2}$. This value, combined with the annual dose calculated above, gives a collective dose per unit electrical energy for uranium mining of approximately 0.05 man rad per MW y.

49. Similar calculations can be performed to assess the collective dose contribution to the lung. The average of the annual reported exposures to radon daughters in 1974 in underground mines in the United States is 1.4 WLM (34). Omitting the exposures reported as zero, under the assumption that they are not really the result of underground work, the annual average becomes 1.9 WLM. The annual average for French miners is 1.3 WLM. As estimated in Annex B, this exposure corresponds to an annual bronchial dose of 1.5-2 rad. The collective dose to the lung per unit electrical energy is therefore about 0.1 man rad per MW y. It should be pointed out, however, that this collective dose to the lung is due to alpha irradiation and cannot be added to that from other steps of the fuel cycle.

B. MILLING AND FUEL FABRICATION

50. The contribution of occupational exposure in milling and fuel fabrication steps of the cycle to the collective dose is minimal. The Committee has received detailed data only from the United Kingdom on fuel enrichment and fabrication carried out at two establishments (47, 53). Table 2 shows these data in summary form. It is difficult to correlate these doses with any particular level of power generation, but if it were assumed that the average annual collective dose over the four years 1972-1975 could be related to the average annual United Kingdom nuclear electrical output over those four years, which was relatively stable at 2612 MW(e) y (39, 85), then the normalized collective dose would be 0.15 man rad per MW(e) y.

TABLE 2. OCCUPATIONAL DOSES TO FUEL ENRICHMENT AND FABRICATION WORKERS IN THE UNITED KINGDOM, 1972-1975

	Annual average dose (rad)				*Annual collective dose[a] (man rad)*			
Occupational description	*1972*	*1973*	*1974*	*1975*	*1972*	*1973*	*1974*	*1975*
Fuel enrichment		0.07	0.04			29 (0)	19 (0)	
Fuel manufacture – chemical processes	0.41	0.61	0.58	0.45	90 (0.7)	134 (1.0)	128 (1.1)	99 (0.6)
Fuel manufacture – fabrication	0.47	0.53	0.58	0.58	56 (0.7)	64 (0.8)	70 (1.0)	70 (0.9)
Fuel manufacture – canning and assembly	0.23	0.28	0.35	0.33	14 (0.4)	17 (0.3)	21 (0.9)	20 (0.5)
Fuel manufacture – maintenance[b]	0.30	0.40	0.40	0.35	150	200	200	175
Total[c]	–	–	–	–	330	440	440	390

[a] The numbers in parentheses are the values of Ω·

[b] Assuming that the dose to maintenance workers is 75% of the dose to production workers.

[c] Assuming annual collective doses from fuel enrichment of 25 man rad in 1972 and 1975.

51. A category for fuel reprocessing and fabrication appears in the occupational exposure summary report of the United States Nuclear Regulatory Commission (18). Since no reprocessing of commercial reactor fuel was carried out in the United States for the years in question (1973-1974), it could be assumed, as an upper limit, that the doses were attributable to fuel fabrication. The data are shown in table 3. A log-probability plot of the dose distribution is shown in figure III. It is a good example of the presumed effect of regulations on the part of the distribution with annual doses exceeding a few rads. If

TABLE 3. COLLECTIVE DOSES TO FUEL REPROCESSING AND FABRICATION WORKERS IN THE UNITED STATES, NRC LICENSEES 1973-1974

Year	*Total number of individuals monitored*	*Number of individuals with measurable exposure*	*Collective dose (man rad)*
1973	10 610	5 056	2 400
1974	10 921	4 617	2 740

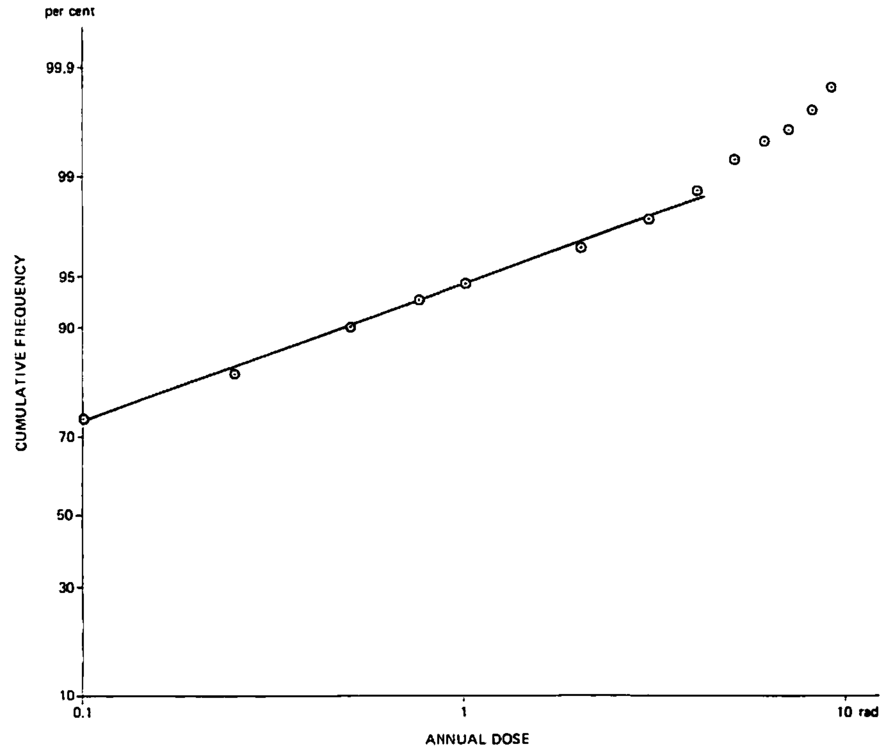

Figure III. Log-probability plot of annual doses to fuel reprocessing and fabrication workers in the United States, 1974

these doses are correlated with the total electricity generated in the same two years (77), then a normalized collective dose of approximately 0.25 man rad per MW(e) y is obtained. Since the United States power reactor industry is rapidly expanding, however, a considerable amount of the fuel fabricated will have been used to fuel reactors that did not contribute significantly to power production in the same year. If this proportion approached 30-40 per cent, as seems likely, then the resulting figure is in reasonable agreement with that for the United Kingdom.

52. In the future, since plutonium will be used in the fabrication of fast reactor fuels, radiological protection of workers at this stage in the fuel cycle will have to adapt itself to the difference of techniques connected to this modification of the fuel nature. The increased handling of plutonium will increase the potential for plutonium intakes. It is not possible for the Committee to judge the importance of this increased potential since it has received no information on doses directly attributable to plutonium fuel fabrication.

C. NUCLEAR POWER REACTORS

53. In contrast to the other stages of the fuel cycle, a reasonable amount of information is now available on doses to personnel at civil nuclear power reactor sites. Most of the information relates to operation of light-water reactors, especially in the United States, but comprehensive data on United Kingdom gas-cooled reactors have also been supplied.

54. A comprehensive summary of occupational radiation exposures in United States light-water cooled reactors has been recently published by the United States Nuclear Regulatory Commission (78). Some data on dose distributions were quoted in the report, but it was indicated that collective doses were obtained either by multiplying the number of people in a range by the mid-point dose in that range and summing the result or, in a small number of cases, by summing the actual doses to all individuals. The collective doses were obtained by including doses to all individuals at the site whether they were plant personnel, utility personnel brought in on a temporary basis, contractor personnel or visitors. The results are summarized in table 4, which shows the annual average collective doses per plant for boiling water reactors (BWRs) and pressurized water reactors (PWRs) from 1969-1975 and the cumulative average collective doses. Although it appeared from the 1973 figure for PWRs that these reactors were starting to experience problems leading to larger personnel doses than anticipated, the considerably reduced figures for 1974 and 1975 lend support to the idea that this may have been transient rather than a trend. The annual average collective doses for BWRs have increased over the same years, but no firm conclusions can be drawn from the figures. The cumulative annual average collective dose per plant for all reactors for the years 1969-1975 is 420 man rad (78). This figure is tending to become stable. Table 48 (appendix II) gives the detailed figures on which these summaries are based.

55. Annual average doses to individuals decreased again in 1974 from the peak in 1972 and remained steady in 1975. The mean number of personnel per plant also showed a decrease in 1974 from the very high figure for 1973, but showed a rise again in 1975. Table 5 shows the annual average doses from 1969-1975 at all United States light-water reactors (78), and figure IV is a log-probability plot of the annual doses (78) for the years 1973, 1974 and 1975. The agreement with a log-normal distribution is not very good, presumably due to a tendency to reduce annual doses approaching or exceeding 5 rad.

TABLE 4. SUMMARY OF COLLECTIVE DOSES AT 32 LIGHT-WATER REACTORS IN THE UNITED STATES, 1969-1975

	Boiling water reactors				*Pressurized water reactors*			
Year	*Number of plants*	*Average rated electrical power capacity (MW)*	*Annual average collective dose (man rad)*	*Cumulative average collective dose (man rad)*[a]	*Number of plants*	*Average rated electrical power capacity (MW)*	*Annual average collective dose (man rad)*	*Cumulative average collective dose (man rad)*[a]
1969	3	116	195	195	4	381	165	165
1970	5	322	130	154	5	403	599	406
1971	7	351	255	200	6	459	340	380
1972	10	450	286	235	8	500	463	409
1973	14	521	330	269	12	575	772	533
1974	14	521	507	332	18	625	364	476
1975	18	626	670	418	26	650	309	421

[a] Collective dose from current year and previous years after 1969 divided by cumulative reactor operating years.

TABLE 5. ANNUAL AVERAGE INDIVIDUAL DOSES AT LIGHT-WATER REACTORS IN THE UNITED STATES, 1969-1975

Year	*Average number of employees per plant*	*Annual average individual dose (rad)*
1969	141	1.06
1970	305	0.98
1971	302	0.96
1972	344	1.20
1973	584	0.85
1974	514	0.74
1975	578	0.80

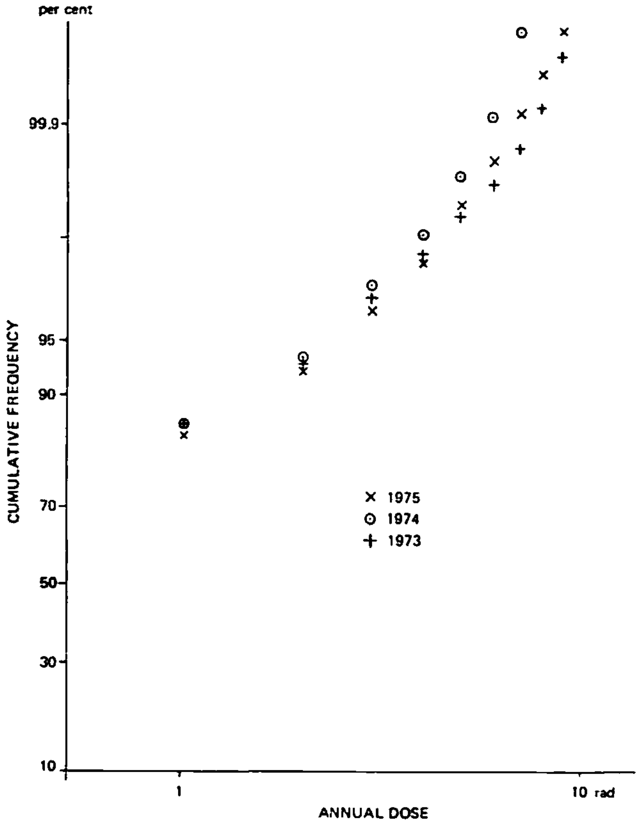

Figure IV. Log-probability plot of annual doses to workers at light-water reactors in the United States, 1973, 1974 and 1975

56. The collective dose per unit electrical energy generated for each station is also given in table 48 (appendix II). These data are summarized in table 6. Murphy *et al.* (78), in quoting these figures, caution that until more experience with light-water reactors (LWRs) is accumulated it will be difficult to draw any conclusions from the data presented. An attempt to relate the collective dose per unit electricity generated with the rated capacity of the units showed no significant correlation. It was found, however, that the collective dose generally increased after the first years of operation.

TABLE 6. ANNUAL NORMALIZED COLLECTIVE DOSE AT LIGHT-WATER REACTORS IN THE UNITED STATES, 1969-1975

(man rad per MW(e) y)

Year	*BWRs*	*PWRs*	*All*
1969	1.75	0.66	0.94
1970	0.63	2.39	1.59
1971	1.36	1.12	1.22
1972	0.81	1.44	1.07
1973	1.00	2.13	1.55
1974	1.75	0.99	1.28
1975	2.03	0.67	0.89

57. The causes of the doses have been carefully analysed in other reports (71, 89). It is apparent that most occupational exposure at reactors is incurred during maintenance rather than routine operation of the reactor. Table 7 shows the percentage of annual exposures received during outages for a number of LWRs (89). This conclusion agrees with the United States Nuclear Regulatory Commission study (78), which lists the following causes of exposure with the percentage of the total collective dose attributable to each:

Routine reactor operation and surveillance	11
Routine maintenance	52
Special maintenance	19
Refuelling	8
In-service inspection	3
Waste processing	7

TABLE 7. PROPORTION OF ANNUAL EXPOSURE RECEIVED DURING OUTAGE AT CERTAIN LIGHT-WATER REACTORS IN THE UNITED STATES

Plant No.	*Year since start-up*	*Outage time (h)*	*Proportion of annual exposure (%)*
1	9	1 406	71
	10	1 257	83
	11	139	27
	12	3 873	67
3	3	1 567	70
	4	1 548	54
	5	2 263	71
4	3	1 432	79
	4	479	74
	5	1 835	69
5	1	4 481	61
	2	2 798	58
	3	2 618	36
	4	2 079	61
10	3	2 131	52
11	1	4 633	97
	2	1 429	81
	3	1 261	84

Source: Reference 89.

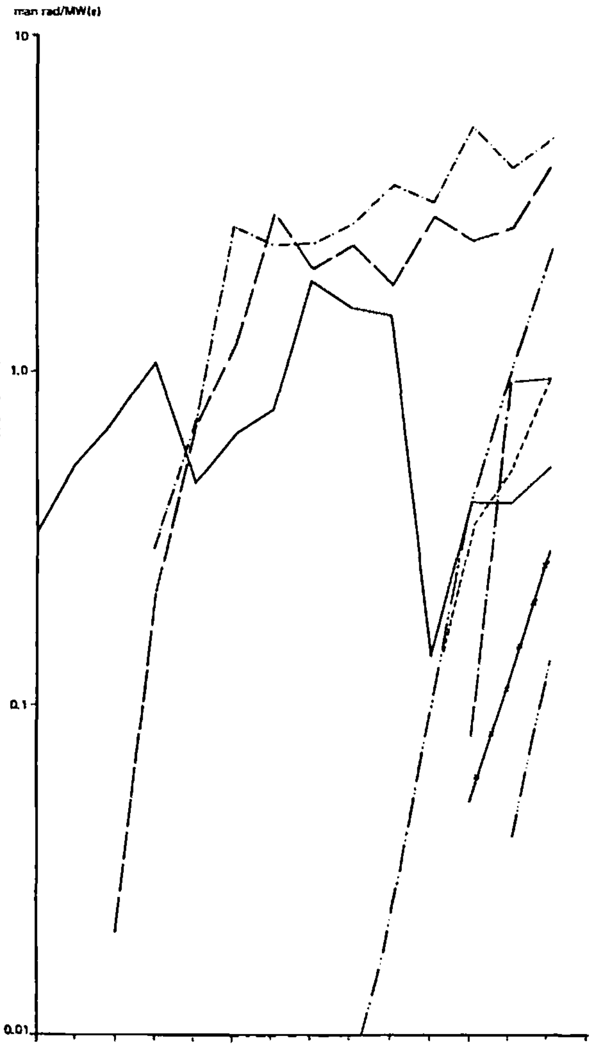

Figure V. Variation of the annual collective dose per unit installed electric power capacity for different boiling water reactors in the United States (89). The plant represented by the solid curve had different capacities during the period, as follows [MW(e)]: 1960-1969, 200; 1970, 200 + 800; 1971-1973, 200 + 2 X 800

58. In the study by Pelletier *et al.* (89), the effect of plant age on annual collective dose was examined (figures V and VI). All the BWR plants showed a marked increase in doses by a factor of two or three each year for the first three to four years, after which the rate of increase dropped considerably. It is suggested that this rapid increase is due to the increasing dose rate encountered for maintenance jobs; these increasing dose rates are due to crud accumulation in pipes, pumps, valves etc. Any change in dose with plant age is not so marked with PWRs as with BWRs after the first year. The annual collective dose at most of the PWRs was dominated by doses received during the inspection and repair of steam generators.

59. The trend in doses and the electricity generated in France is shown in table 8 for the period 1964-1974 (12, 88). The results of individual dosimetry on approximately 2000 workers show good stability of the annual average dose between 1970 and 1975. Figure VII shows the variation of the frequency of annual doses ⩾0.5 rad over the period 1964-1975 (12, 88). The collective dose has been within the range 0.5-1.0 man rad per MW(e) y from 1966 to 1974. Detailed dose distributions to workers at French nuclear power stations for 1970 (28) and 1971 (29) are shown in table 49 (appendix II),

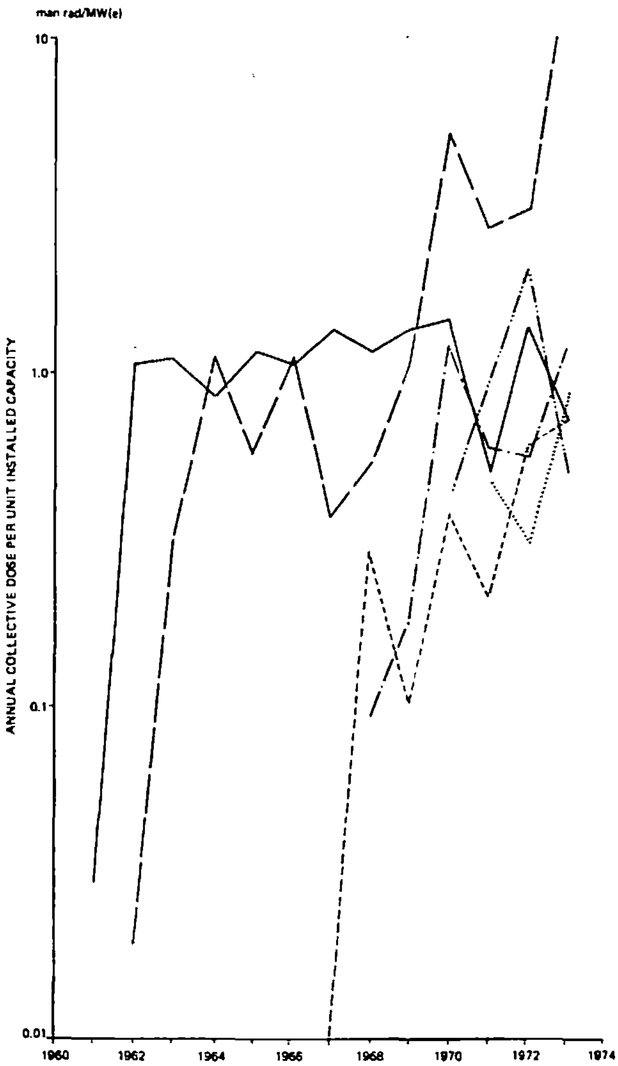

Figure VI. Variation of the annual collective dose per unit installed electric power capacity for different pressurized water reactors in the United States (89)

TABLE 8. DATA RELATING TO OCCUPATIONAL DOSES AT NUCLEAR POWER PLANTS IN FRANCE, 1964-1974

	1964	*1965*	*1966*	*1967*	*1968*	*1969*	*1970*	*1971*	*1972*	*1973*	*1974*
Number of workers with film badges	333	434	495	578	758	1 167	1 509	1 644	1 593	1 560	1 598
Installed electrical capacity (MW)	80	270	270	820	820	1 546	1 546	2 085	2 625	2 565	2 565
Net electrical energy produced (MW y)	17	40	103	229	282	440	522	823	1 500	1 512	1 444
Annual average dose (rad)	0.16	0.16	0.18	0.30	0.28	0.30	0.34	0.39	0.48	0.47	0.55
Annual collective dose (man rad)	53	72	89	173	212	350	513	648	776	733	883
Collective dose per unit energy produced (man rad per MW(e) y)	3.1	1.8	0.87	0.76	0.75	0.80	1.02	0.79	0.52	0.48	0.61

Sources: References 12, 88.

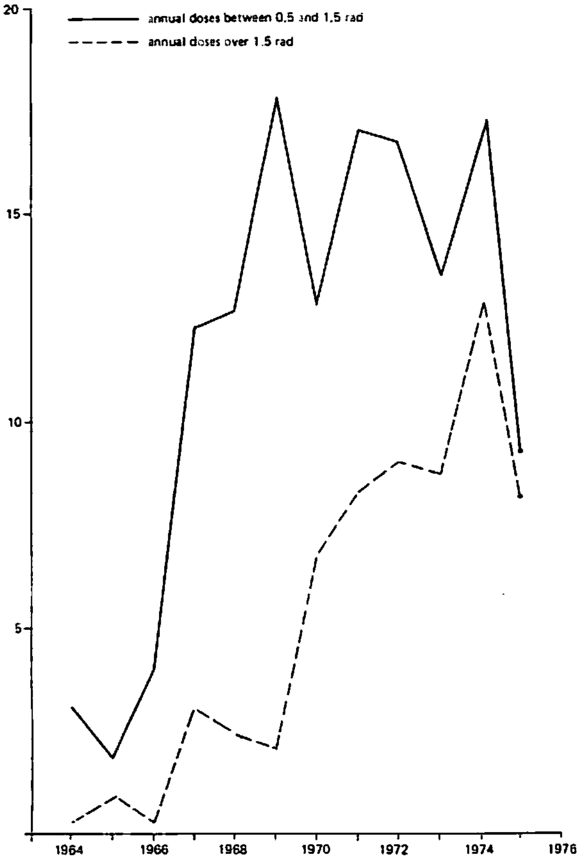

Figure VII. Variation of the frequency of individual annual doses ⩾0.5 rad at reactors in France (12, 88)

together with the dose distribution for 1974 (12). The Ω values calculated by fitting a log-normal curve to these distributions are 1.5, 1.2 and 1.7 for 1970, 1971 and 1974, respectively.

60. Many other countries have reactors of a type similar to those in the United States. They have less experience and fewer operating plants than the United States, but the data reported support, for the most part, the United States figures for doses associated with the operation and maintenance of LWRs.

61. Data from the Federal Republic of Germany for the period 1973-1975 are given in table 50 (appendix II) (72a). The reported collective doses are obtained by summation from the measured individual doses; the mean values are arithmetical mean values. The average individual doses and collective doses are quoted separately for the plant personnel employed permanently in the nuclear power plant and for the external personnel working in the plant temporarily and during fixed periods. The information covers all commercial nuclear power plants currently in operation in the Federal Republic of Germany. The average individual doses for all nuclear power plants in the Federal Republic of Germany are summarized in table 9. For all personnel, doses are of the same order of magnitude as for light-water reactors in the United States. The indicated average doses to external personnel are always less than those to plant personnel. The reason is that some of the external personnel work in several plants and are therefore quoted several times when the total for all plants is made up. The annual average dose to external personnel shown in the table is therefore an underestimate.

62. Some data have been provided on doses in Swedish power plants (69a). These are shown in detail in table 51 (appendix II). It is apparent that most of the collective dose is received by contractors' employees rather than direct employees of the utility; however, the annual

TABLE 9. SUMMARY OF DOSES TO WORKERS AT NUCLEAR POWER PLANTS IN THE FEDERAL REPUBLIC OF GERMANY, 1973-1975

	Plant personnel			*External personnel*			*All personnel*		
Year	*Number of persons*	*Annual collective dose (man rad)*	*Annual average dose (rad)*	*Number of persons*	*Annual collective dose (man rad)*	*Annual average dose (rad)*	*Number of persons*	*Annual collective dose (man rad)*	*Annual average dose (rad)*
1973	1 108	1 270	1.15	2 586	1 240	0,48	3 694	2 520	0.68
1974	1 471	1 300	0.89	3 251	1 650	0.51	4 722	2 950	0.62
1975	1 549	1 380	0.89	3 225	2 120	0.66	4 774	3 500	0.73

TABLE 10. ANNUAL COLLECTIVE DOSE AND COLLECTIVE DOSE PER UNIT ELECTRICAL ENERGY GENERATED AT THREE ITALIAN POWER PLANTS

	Latina		*Trino*		*Garigliano*	
Year	*Annual collective dose (man rad)*	*Collective dose per unit nergy generated (man rad per MW(e) y)*	*Annual collective dose (man rad)*	*Collective dose per unit energy generated (man rad per MW(e) y)*	*Annual collective dose (man rad)*	*Collective dose per unit energy generated (man rad per MW(e) y)*
1963	57	1.56	–	–	27	[a]
1964	78	0.45	7.4	0.54	75	0.89
1965	88	0.51	27	0.23	102	0.92
1966	77	0.46	28	0.16	108	1.16
1967	100	0.55	51	0.69	146	1.39
1968	85	0.48	31	[a]	148	1.26
1969	87	1.52	109	[a]	144	1.07
1970	80	0.59	53	0.38	202	2.42

[a] No electricity generated.

average doses to the two groups are comparable and quite low, rarely exceeding 0.20 rad. There is as yet insufficient operating experience on these reactors to establish any trends, but the overall annual collective doses for the two larger operational stations in 1975 were 84 and 166 man rad, comparable with the lower end of the range covered by United States reactors.

63. There are some data on occupational doses for three Italian power plants (24). It is apparent that radiation protection staff in general received the highest doses; however, they are fewer in number than the maintenance staff. There was a considerable amount of maintenance work done at Trino Vercellese during 1967 and 1970. The annual collective dose from 1963 to 1970 at the plants is shown in table 10. The variation in collective dose per unit electrical energy generated is rather large, but the values cover the range of the United States figures.

64. Data on doses to contract workers at two Swiss nuclear power stations are shown in table 52 (appendix II) (60). The annual collective doses at the two stations were 110 and 82 man rad, respectively, in 1975 for 194 and 175 workers on each station, and the values for Ω were 1.4 and 1.3.

65. Data have been supplied by Argentina on the occupational doses received at the nuclear power plant at Atucha in 1974 and 1975 (21, 25). These are shown in detail in tables 53 and 54 (appendix II). The annual collective doses due to external exposure in the two years 1974 and 1975 were 83 and 138 man rad, with average annual doses of 0.31 and 0.44 rad. The Ω values for the two years were 0.4 and 0.8. The installed generating capacity of the station is 320 MW(e) and the energy generated in the two years was 118 and 287 MW(e) y. Doses from exposure to tritium were in general small and, since these are likely to be overestimates, are only thought to add about 20 per cent to the above collective dose estimates. The normalized collective dose for this station is therefore 0.6-0.8 man rad per MW(e) y.

66. Canadian reactors of the CANDU type have now been operating for 12 years. Sufficient experience has been accumulated at Pickering, where four units were brought into service between 1971 and 1973, to enable some conclusions to be drawn on occupational doses at stations of this type. Table 11 summarizes the information on annual collective doses at Pickering from commissioning up to 1974 (125). It may be seen that with this type of reactor some 20-30 per cent of the collective dose is a result of internal doses from tritium. The overall figures are again comparable with those for United States light-water reactors (see tables 4 and 6).

TABLE 11. COLLECTIVE DOSES AT THE NUCLEAR POWER PLANTS AT PICKERING, CANADA, 1971-1974

Year	*Annual collective doses (internal and external) (man rad)*	*Fraction due to internal doses from tritium (%)*	*Collective dose per unit energy generated (man rad per MW(e) y)*
1971	198	24	0.60
1972	993	18	1.70
1973	899	30	0.55
1974	1 613	30	1.10
Average	926	26	0.90

67. The United Kingdom commercial nuclear power stations are of the gas-cooled graphite-moderated reactor type (GCR). Complete data on occupational exposures are shown in table 55 (appendix II) and in summary form in table 12 (39, 85). It can be seen that the annual average doses, collective doses and collective doses per unit energy supplied to the grid are considerably less at the newer stations (Oldbury, Sizewell, Wylfa) than at the older ones (Berkeley, Hinkley Point, Hunterston). The high collective doses at Trawsfynydd and Hinkley Point during this period were due to cooling-pond problems. The normalized collective dose due to electricity supplied to grid by all United Kingdom reactors over the three years considered was 0.73 man rad per MW(e) y. This should be regarded as representative of the current situation rather than indicative of future expectations. Data on eye doses at five United Kingdom reactors from 1971-1973 have been supplied. The detailed figures are shown in table 56 (appendix II).

68. A gas-cooled reactor of a type similar to the older United Kingdom reactors is installed at Tokai in Japan.

TABLE 12. SUMMARY OF OCCUPATIONAL DOSES AT UNITED KINGDOM GAS-COOLED NUCLEAR POWER PLANTS, 1972-1974

	Annual average dose (rad)			*Annual collective dose[a] (man rad)*			*Collective dose per unit electrical energy supplied to grid (man rad per MW y)*		
Plant	*1972*	*1973*	*1974*	*1972*	*1973*	*1974*	*1972*	*1973*	*1974*
Berkeley	0.69	0.72	0.70	271 (0.8)	302 (1.3)	284 (1.0)	1.21	1.27	1.27
Bradwell	0.40	0.29	0.32	164 (0.1)	146 (0.1)	129 (0.1)	0.79	0.80	0.63
Hinkley Point	0.35	0.32	0.31	253 (0.8)	410 (1.0)	514 (0.01)	0.74	1.53	1.47
Trawsfynydd	1.12	0.72	0.43	575 (2.3)	430 (2.1)	260 (1.0)	2.12	1.85	0.70
Dungeness	0.25	0.20	0.20	135 (0)	129 (0)	135 (0)	0.37	0.35	0.35
Sizewell	0.11	0.13	0.16	53 (0)	84 (0.3)	82 (0.5)	0.17	0.25	0.23
Oldbury	0.17	0.17	0.17	75 (0)	73 (0)	71 (0)	0.25	0.25	0.22
Wylfa	0.12	0.10	0.12	37 (0)	62 (0)	72 (0)	0.13	0.21	0.17
Hunterston	0.54	0.40	0.50	364 (0.1)	277 (0.1)	360 (0.4)	1.61	1.25	1.48

[a] The number in parentheses is the Ω value.

The annual collective doses at this reactor in 1973 and 1974 were 131 and 65 man rad, leading to values for the collective dose per unit electrical energy produced of 1.11 and 1.16 man rad per MW y (41).

D. FUEL REPROCESSING

69. The major commercial fuel-reprocessing installation which has been in operation over recent years is in the United Kingdom at Windscale, Cumbria. Table 13 shows the annual average individual doses and the annual collective doses from 1971-1975 (48). The dose distributions for these years are shown in table 57 (appendix II); the Ω values shown in table 13 were calculated from them. Figure VIII shows a typical distribution indicating the effect of dose limits. The procedure used was therefore to fit a log-normal curve to the distribution up to 1.5 rad but to use the actual results above that value.

TABLE 13. OCCUPATIONAL DOSES TO FUEL-REPROCESSING WORKERS AT WINDSCALE, UNITED KINGDOM, 1971-1975

Year	*Annual collective dose (man rad)*	*Ω*	*Annual average dose (rad)*
1971	3 050	2.2	1.20
1972	3 380	2.3	1,27
1973	3 250	2.3	1.25
1974	3 440	2.3	1.23
1975	4 030	2.2	1.19

70. It is very difficult to correlate the collective doses with a particular rate of electricity generation, but assuming again that the doses incurred at Windscale over the years 1972-1975 could be related to the average electrical output over those years, as in paragraphs 50-51, and making an allowance for the 8-per-cent fuel throughput from overseas (83), then the collective dose

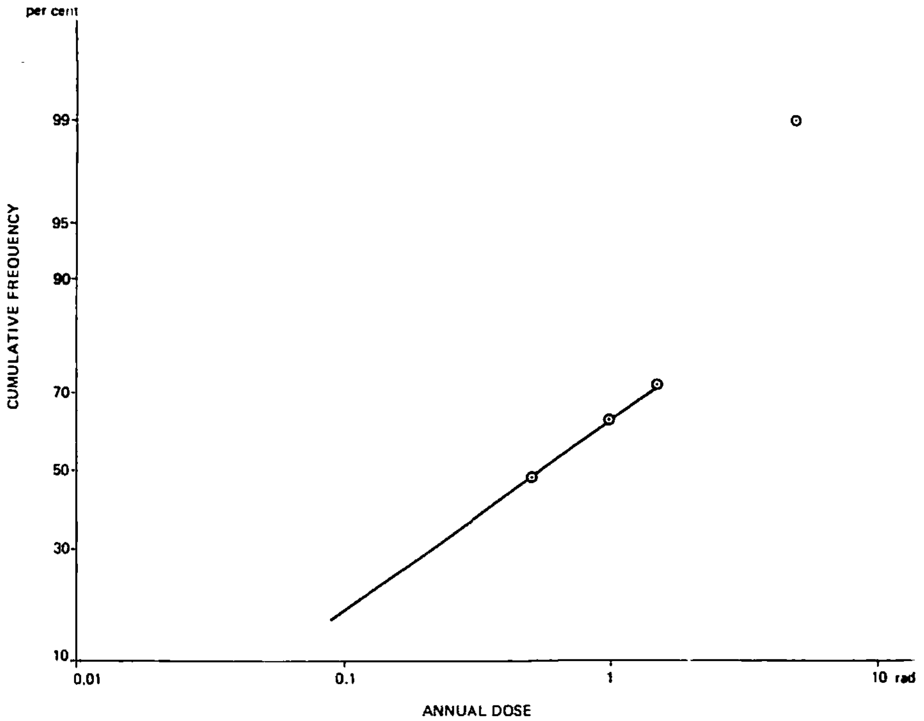

Figure VIII. Log-probability plot of annual doses to fuel-reprocessing workers at Windscale, United Kingdom, 1975 per unit energy produced would be 1.2 man rad per MWI(e) y. It cannot be sufficiently emphasized that this figure is historical and refers to past practices in the reprocessing of natural uranium, Magnox fuel elements. It is unlikely to be indicative of future collective doses per unit energy produced, particularly for oxide fuel reprocessing.

71. Some information has been provided by Belgium (73) on the dose distribution of workers in fuel fabrication, reprocessing and research for 1973. These data are shown in table 58 (appendix II), where the relevant category is "producers". The annual collective dose is 690 man rad with an Ω value of 1.8, and the annual average dose is 0.32 rad. Unfortunately, no indication of fuel throughput was available so no estimate can be made of collective dose per unit energy produced.

E. TRANSPORTATION

72. Occupational exposures of workers involved in transportation cannot be obtained directly, as many of these workers are not subject to individual monitoring and those who are may also be involved in other jobs within the industry. Dose calculations are, therefore, based on assumptions as to the dose rates at different distances from the packages and the times spent by workers in various operations. As an example, the doses to truck drivers from the transportation of unirradiated fuel have been estimated, using the following assumptions (115): the external dose rate at 1 m from the truck and in the vehicle cab are unlikely to exceed 0.1 and 0.01 mrad/h, respectively; the average distance of a journey is 1600 km; two drivers spend about 20 h in the cab and about 1 h outside the truck at a distance of 1 m during a journey.

73. With reasonable assumptions such as those given above, it can be estimated that each driver could receive about 0.3 mrem per shipment. Under normal conditions the estimated collective doses to transport workers for light-water reactors in the United States are as follows (man rad per MW(e) y): transport of unirradiated fuel, 10^{-5}; transport of spent fuel, $2\ 10^{-3}$; transport of solid waste, 10^{-3} (115). For GCRs in the United Kingdom, values of about $3\ 10^{-4}$ for the transport of unirradiated fuel and $2\ 10^{-3}$ for spent fuel have been estimated (123).

F. RESEARCH AND DEVELOPMENT

74. If the nuclear fuel cycle is to be considered as a whole, then some account must be taken of exposures in the research and development organizations devoted wholly or largely to servicing the industry. It is difficult to separate that part of the work of, for example, the United Kingdom Atomic Energy Authority or the United States Energy Research and Development Administration directly connected with the nuclear power industry from that part connected with other aspects of radioactivity. However, it seems likely that the bulk of the occupational exposures are connected with the nuclear power support work.

75. Overall dose distributions for United States Atomic Energy Commission employees and contractors are shown in table 59 (appendix II) for the years 1971-1973. These were obtained from the reports of the United States Atomic Energy Commission Central Repository of Industrial Radiation Exposure Information (111, 112, 113). Because of the very large percentage of doses in the 0-1 rad category and the large number of visitors included in the "contractor" category, it is unusually difficult to estimate average doses. A breakdown of the doses below 1 rad was attempted by Klement *et al.* (64) for the 1969 data relating to 102 918 employees, on the basis that the percentage in each division below 1 rad was the same as that reported for the Atomic Energy Commission and some agreement state licensees. A log-probability plot of these data is shown in figure IX, in which the points have been fitted by a straight line up to a dose of 2 rad. The annual average dose has been estimated from this line as 0.17 rad. Using the same technique on the 1973 data, with the visitors discounted on the basis that they rarely receive any dose, the log-probability plot of figure X is obtained, again with a straight-line fit up to a dose of 2 rad, from which an annual average dose of 0.14 rad is obtained. The annual collective dose is therefore 13 300 man rad with a value for Ω of 1.1.

76. Most of the nuclear research establishments in the United Kingdom are operated by the United Kingdom Atomic Energy Authority. Table 14 summarizes the doses from 1972 to 1974 (33). The collective dose recorded includes the estimated dose added for lost badges and is used to calculate the average dose. In addition, the Central Electricity Generating Board runs a research laboratory at Berkeley to support the commercial exploitation of nuclear power. The annual doses at this establishment are also summarized in table 14 (85). The detailed dose statistics from each organization are shown in tables 60 and 61 (appendix II). Since these data did not approximate a log-normal distribution very closely, the value of Ω was calculated directly from the dose distribution assuming mid-point doses for ranges above 1.5 rad. For the Central Electricity Generating Board values, only a small number of persons receive annual doses exceeding 1.5 rad, so changes in the Ω value are not necessarily indicative of a trend.

TABLE 14. OCCUPATIONAL DOSE AT RESEARCH AND DEVELOPMENT ORGANIZATIONS IN THE UNITED KINGDOM CONNECTED WITH THE NUCLEAR POWER INDUSTRY, 1972-1974

Organization	*Year*	*Annual collective dose (man rad)*	*Ω*	*Annual average dose (rad)*
United Kingdom Atomic Energy Authority	1972	5 020	2.1	0.71
	1973	4 450	1.9	0.66
	1974	3 960	1.9	0.57
Central Electricity Generating Board	1972	126	0.5	0.24
	1973	109	0.3	0.18
	1974	99	0.1	0.15

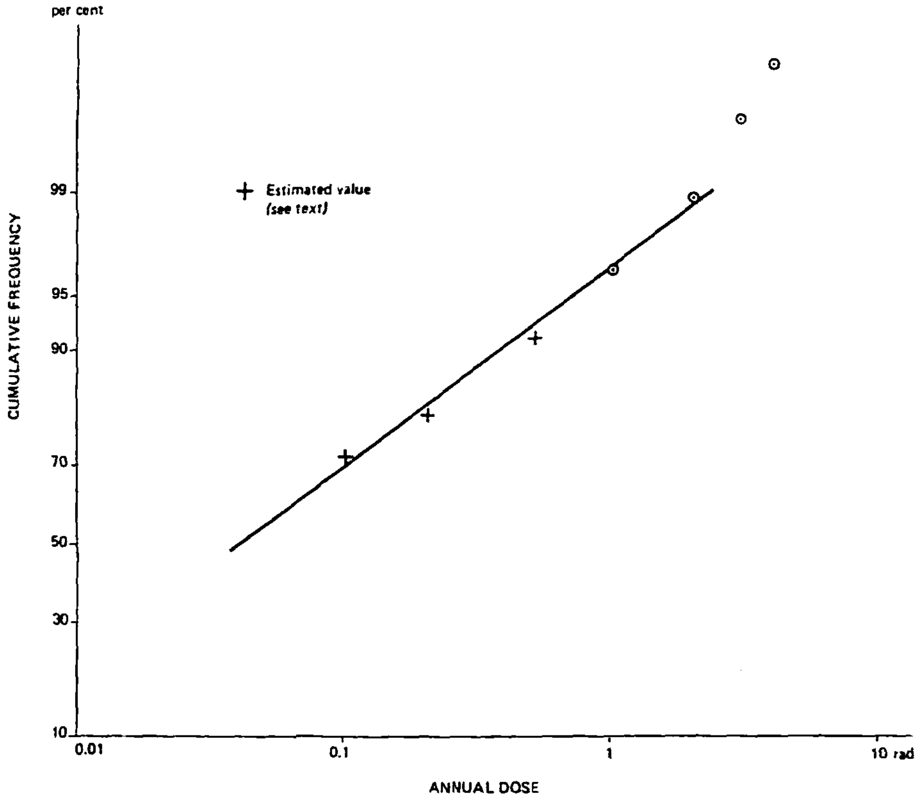

Figure IX. Log-probability plot of annual doses to radiation workers at United States Atomic Energy Commission sites, 1969

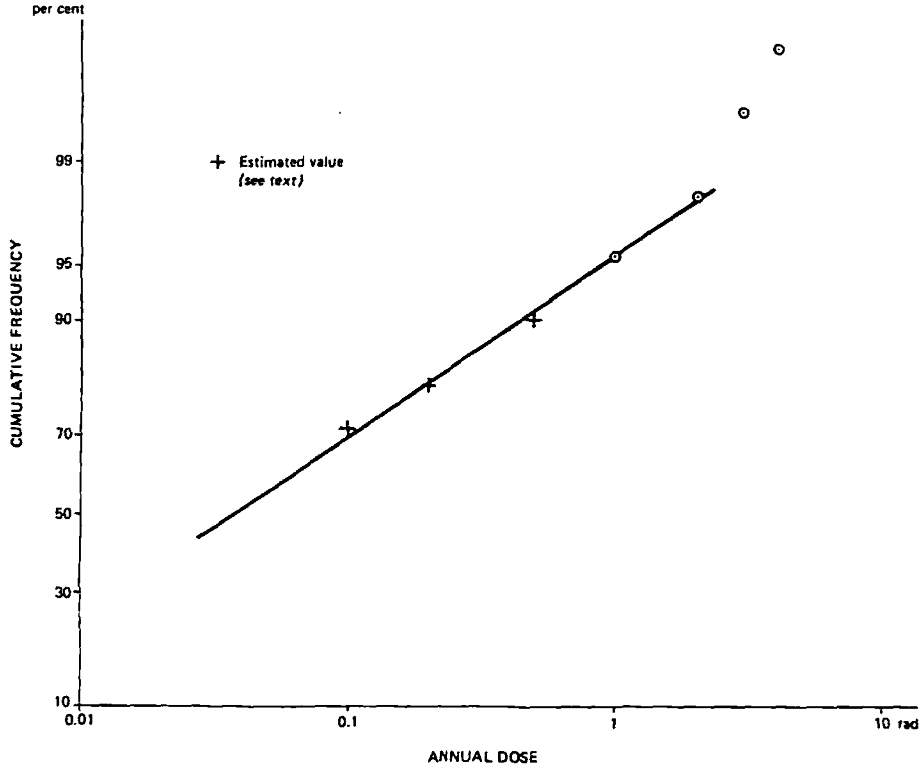

Figure X. Log-probability plot of annual doses to radiation workers at United States Atomic Energy Commission sites (excluding visitors), 1973

77. Data have been supplied by Argentina (21, 25) on the occupational dose received by personnel of the Comisión Nacional de Energía Atómica (CNEA) for the years 1968-1974. These are shown in detail in table 53 (appendix II) and the extracted parameters are given in table 15.

78. Data on average doses for the years 1970-1973 have been supplied for the Indian Department of Atomic Energy (50). These are shown in table 62 (appendix II). The annual average doses in 1972 and 1973 were approximately 0.75 rad and the annual collective doses in those two years about 4000 man rad.

TABLE 15. OCCUPATIONAL DOSES AT CNEA, ARGENTINA, 1968-1974

Year	*Annual collective dose (man rad)*	*Ω*	*Annual average dose (rad)*
1968	122	1.0	0.17
1969	87	0.4	0.10
1970	85	0.7	0.09
1971	116	0.9	0.12
1972	93	0.8	0.10
1973	200	1.7	0.22
1974	135	1.1	0.16

79. In Thailand, the annual average doses in 1974 at a research reactor and in general research were 0.58 rad. These data led to a value for the annual collective dose of 70 man rad (94). The complete data are shown in table 63 (appendix II).

80. The doses to atomic energy research workers in Israel are shown in table 64 (appendix II) (7). The average annual dose over the years 1970-1972 was about 0.1 rad, leading to an annual collective dose of 80-90 man rad.

G. SUMMARY OF COLLECTIVE DOSES FROM THE NUCLEAR POWER INDUSTRY

81. On the basis of the data supplied to the Committee and the analyses performed on these data, the portions of the nuclear fuel cycle which contribute the majority of the collective dose per unit energy generated are reactors, fuel reprocessing and the associated research and development. Uranium mining, milling and fuel fabrication together with transportation of both irradiated and unirradiated fuel give rise to a collective dose to the whole body per unit energy generated of only 0.2 man rad per MW(e) y. An additional collective dose to the lungs of uranium miners per unit energy generated of 0.1 man rad per MW(e) y is also delivered. Annual average doses and collective doses vary considerably both between different reactors in the same year and at the same reactor in different years. In general these variations are greater than those between different reactor types, e.g., light-water reactors and gas-cooled reactors. Nonetheless, a sufficient number of reactors are now in operation and have been operating long enough for an overall average figure for collective dose per unit energy generated to be derived, one that will not be susceptible to rapid change. It appears from all the information supplied that a value of 1.0 man rad per MW(e) y is a reasonable general figure. Fuel reprocessing undoubtedly will contribute significantly to the overall occupational dose, but so far it is not practised commercially on a wide scale. Based solely on the United Kingdom data, a value of 1.2 man rad per MW(e) y may be taken. This figure is only representative of past experience with the reprocessing of Magnox fuel and is unlikely to be appropriate for future reprocessing, particularly of oxide fuels. Making the assumption that all the doses received in such diverse organizations as the United Kingdom Atomic Energy Authority or the United States Energy Research and Development Administration are all received in support of the nuclear power industry, research and development emerges as the largest single contributor to the collective dose per unit energy generated with an average value for this quantity of 1.4 man rad per MW(e) y. This assumption is also cautious; even if it is true, the proportion of research and development required would be expected to decrease as the industry matures.

VI. DOSES IN OCCUPATIONS OTHER THAN THE NUCLEAR POWER INDUSTRY

82. As in chapter V, summaries or extracted parameters are presented in this chapter with more detailed information given in appendix II. It is also the intention to present in this chapter overall summaries of the situations; more detailed information on particular types of workers, especially those receiving higher than average doses, is presented in chapter VII.

83. In the case of the nuclear power industry, the beneficial output could readily be defined as electricity supplied to the grid. In this section, however, the beneficial output cannot be so easily identified, and even where it could be identified, data on the magnitude of the output and its relation to doses are normally not supplied.

A. MEDICAL USES OF RADIATION AND RADIOACTIVITY

84. It is perhaps in the process of assessing doses to medical workers that the difficulties noted in paragraphs 9 and 10 become most acute. The doses received by different parts of the body will often be quite different, and it is not always clear to what organ or organs the reported dose corresponds. The Committee has perforce had to assume that reported doses with no other indication were average whole-body doses. In all countries which reported, monitoring of doses to workers involved with medical uses of radiation or radioactivity is carried out by a number of establishments ranging from individual hospitals to large commercial or governmental specialized personnel-monitoring services. Usually, the results are reported to the employer but are not collated nationally. That, and the fact that medical workers are employed in small numbers in each of a large number of establishments rather than concentrated in a few easily identified centres as in the nuclear power industry, means that the collection of dose information is difficult. Ensuring that the data is comprehensive and representative is almost impossible. Hence, in this section the Committee can only present that information which is available, and it is hoped that the picture it forms is not too distorted.

85. The problem is exemplified in the information supplied by the United Kingdom, which does at least provide an estimate of the magnitude of the total problem (110). Medical workers in the United Kingdom are monitored by a number of different laboratories and individual hospitals. Data were obtained from some of these. It was estimated that there were at least

18 000 medical workers involved with radiation: there could be several thousand more. The annual dose distribution for 6552 of these workers in 1974 is shown in figure XI (23, 27, 31, 43, 69, 81, 105, 109, 110). The annual collective dose to these workers is 1370 man rad with a Ω value of 0.90 and an annual average dose of 0.21 rad. If it is assumed that these parameters are representative and that the total number of workers is 20 000, then the total annual collective dose to medical workers in the United Kingdom in 1974 was about 4000 man rad.

86. Some local or sample surveys have been reported for the United States. Figure XII shows the dose distributions of monitored individuals in the state of Illinois, both in hospitals and clinics and in the surgeries of doctors or dentists (16). The hospital and clinic population has enough people in the higher dose range for the presumed effect of the maximum permissible dose limit to be seen above annual doses of 1 rad. The annual average dose reported for these hospitals and clinics in 1973 was 0.074 rad; however, reporting is required in Illinois only for those employees whose quarterly doses may exceed 0.312 rad (64). Thus, the actual distribution of all monitored workers would probably be on a line lying to the left of that in figure XII. Figure XIII shows a sample of three annual recorded dose distributions for the smaller population of Mercy Hospital, Pittsburgh. All the dose distributions at this hospital from 1965 to 1974 were consistent with log-normal functions (103).

87. In the survey of ionizing radiation doses in the United States (64), it was recognized that "the most tenuous estimate developed in this study is the mean annual dose of non-federal employees exposed during the use of radiation in diagnostic and therapeutic medical and dental radiology". The data available to the authors consisted of information from three states, including the data from Illinois cited above. A survey in 1969 of 663 medical x-ray workers in the state of Wisconsin indicated an average collective dose rate of 4.15 man rad per week (64). Assuming that each individual worked for 50 weeks per year, the annual average dose would be 0.313 rad. The data for Illinois in 1970 shown in table 65 (appendix II) give an estimated annual average dose of 0.324 rad to medical workers. In the state of Maine in 1965, the average monthly dose for all categories of radiation workers was 0.020 rad. Using the foregoing data, Klement *et al.* assigned an annual average dose of 0.32 rad per non-federal medical x-ray worker (64); this mean was applied to 194 541 medical x-ray workers.

88. A survey of personnel occupationally exposed in radium therapy was conducted by the state government of Wisconsin and made available to the United States Public Health Service. From this study it was estimated (64) that there may be in the United States up to 38 000 individuals occupationally exposed in radium treatment who are not otherwise reported. The estimated number of radium treatments in Wisconsin was 800 per year. From 37 treatments monitored, the average dose was 0.5 rad per treatment or 400 man rad y^{-1} from all treatments. This resulted in an annual average dose of 0.54 rad for the 740 medical workers in Wisconsin. This average was assumed to apply nationally.

89. A more recent survey of occupational doses to personnel in United States nuclear medicine departments

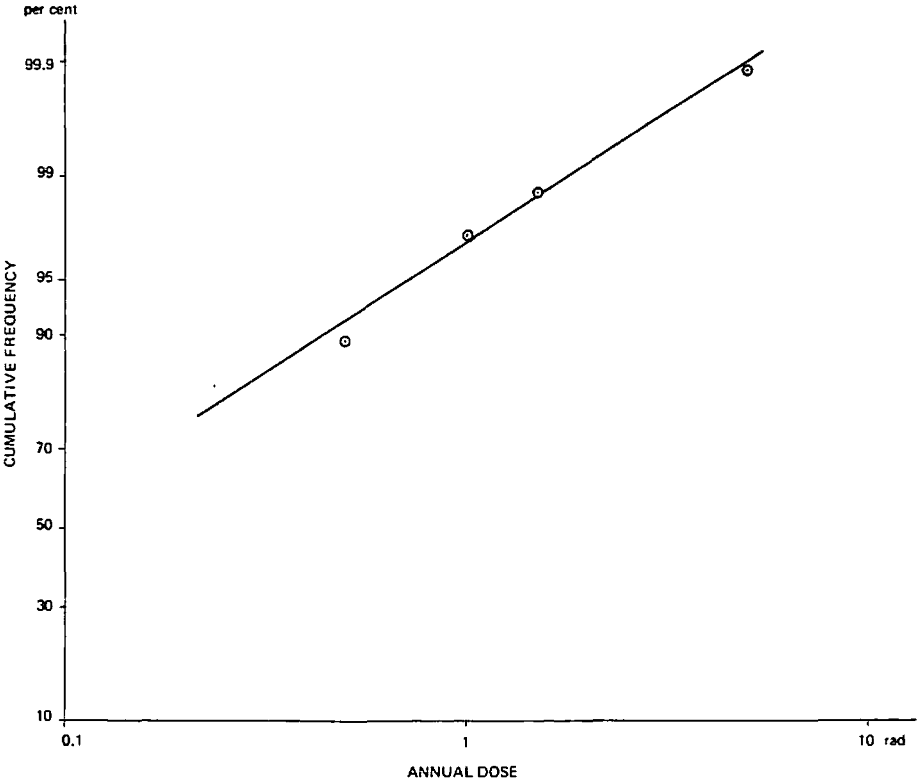

Figure XI. Log-probability plot of the annual doses to a sample of 6552 medical workers in the United Kingdom, 1974

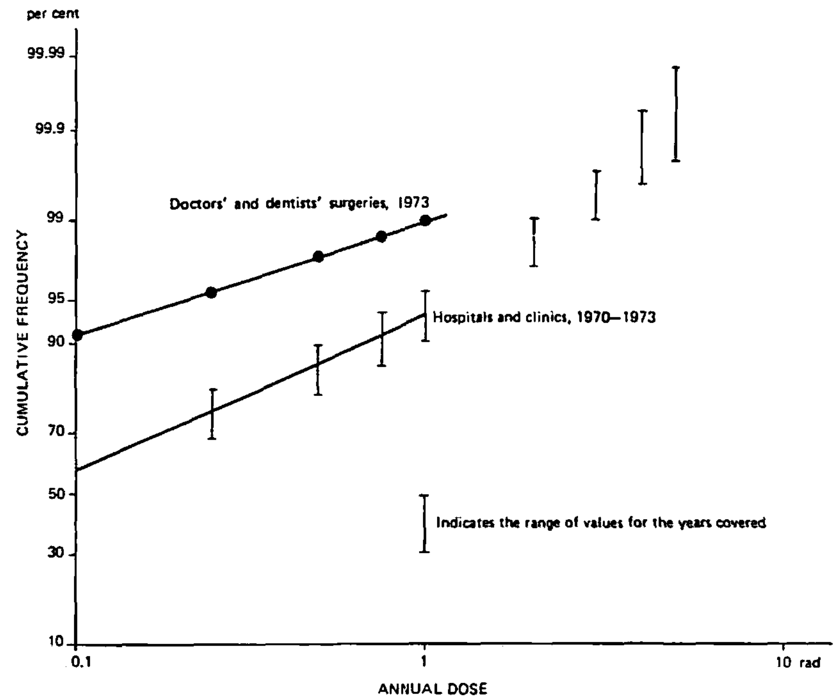

Figure XII. Log-probability plot of annual doses to workers at medical and dental institutions in the state of Illinois, United States, 1970-1973

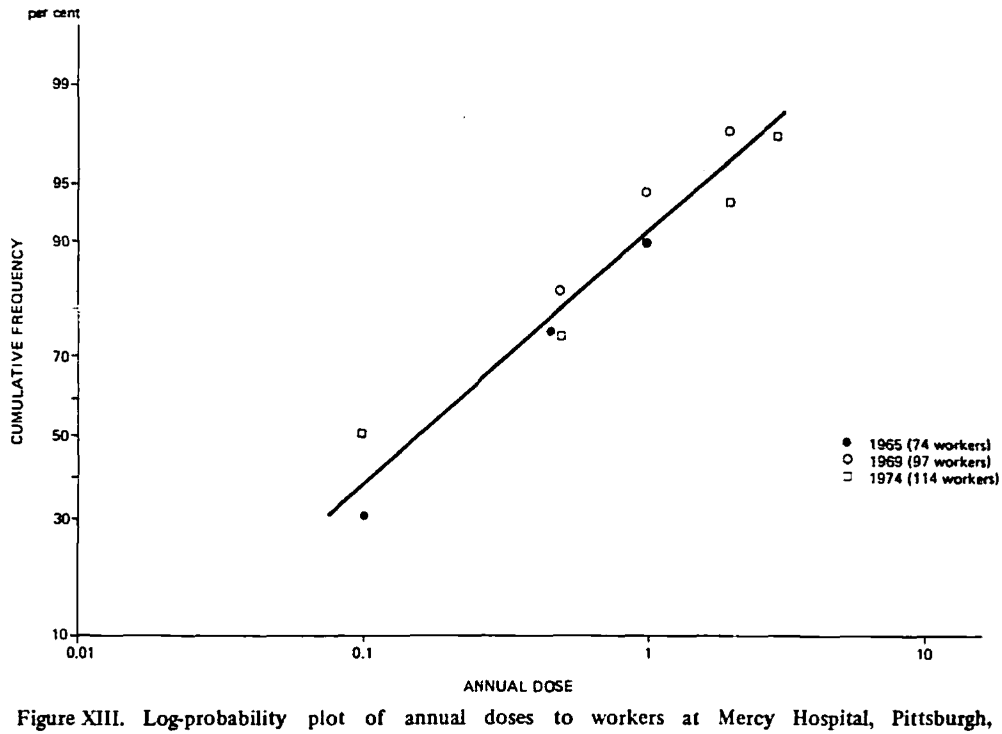

Figure XIII. Log-probability plot of annual doses to workers at Mercy Hospital, Pittsburgh, Pennsylvania, United States, 1965, 1969 and 1974

has been carried out by the Scientific Committee on Radiation Protection of the American Association of Physicists in Medicine (8). Forty-seven hospitals were included in the study; both teaching and non-teaching institutions were included in varied geographical locations, although no attempt was made to obtain a representative sample of the whole country. The method was to send a questionnaire and analyze the results. One outstanding feature of this survey was that an attempt was made to relate the doses to some measure of the workload. The measure selected was the total amount of ^{99m}Tc injected. It was assumed tha the total work of the department results in the total collective dose to the workers, regardless of the distribution of work and dose among the personnel. As part of the questionnaire, it was established that in most institutions ^{99m}Tc accounted for more than 90 per cent of the total activity of radionuclides administered, so the use of this as a measure seemed reasonable. Some results of the survey are shown in table 16: each figure in this table is an independent average of the values reported for that quantity. The total amount of ^{99m}Tc injected and therefore the amount injected per employee increased by a factor of four from 1968 to 1973. The collective

TABLE 16. SOME RESULTS OF A SURVEY OF NUCLEAR MEDICINE DEPARTMENTS OF 47 HOSPITALS IN THE UNITED STATES, 1968-1973

	1968	*1969*	*1970*	*1971*	*1972*	*1973*
Average number of full-time employees in nuclear medicine	7.52	8.23	6.52	6.48	7.06	7.38
Annual average collective dose (man rad)	1.68	1.89	2.39	2.47	2.70	2.77
Annual average individual dose (rad)	0.38	0.37	0.45	0.45	0.49	0.48
Annual average activity of ^{99m}Tc injected (Ci)	6.6	8.2	11.0	13.4	16.5	25.8
Annual average collective dose per unit ^{99m}Tc injected (man rad Ci^{-1})	0.47	0.34	0.35	0.27	0.30	0.11

dose did not increase proportionately, with the result that the average dose per unit workload decreased by about 70 per cent from 1970 to 1973. The results for 1968 and 1969 may be biassed, as only a small number of hospitals responded for these years. Tentative correlations were established between higher doses per unit workload and overcrowding (laboratories with less than 14 m^2 per person) and small numbers of employees (less than five). It was also noted that over the 47 hospitals the collective dose per unit workload varied by more than a factor of 60. The higher values could be reduced significantly if more care were taken and more attention paid to the details of shielding and patient positioning. It was concluded that with proper attention to good radiation protection practices, it appears feasible to reduce collective doses to nuclear medicine personnel per unit quantity of ^{99m}Tc injected to an annual average of less than 0.05 man rad Ci^{-1}. Despite the usefulness of this survey, it did not give a figure for the overall doses in the United States. However, Brodsky has estimated the average annual dose to nuclear medicine workers as 0.5-0.6 rad, leading to a total annual collective dose of 7000 man rad (17).

90. The Committee has received a great deal of information from the Health Protection Branch of the Health and Welfare Department in Canada (4). The data are grouped according to job classification and provide comprehensive information for 1974. They are summarized in table 17, which is based on a log-probability analysis of each set of figures. From this it can be seen that the largest annual collective dose, over 500 man rad, is due to diagnostic radiology, with a further 73 man rad from therapeutic radiology. A collective dose of 160 man rad is received by nurses, ward aides and orderlies. Physicians received 80 man rad and technicians 87. All other contributions to the collective dose were relatively low. The average annual doses were relatively low in all cases (<0.2 rad) and none of the Ω values were very much greater than 1.0, indicating that the collective dose was received at annual doses roughly similar to those of the reference distribution. The total annual collective dose for human medical work (excluding dentistry) in Canada in 1974 is about 1000 man rad.

91. Some information has been supplied on film badge doses in Denmark in 1974 (118). This is reproduced in table 66 (appendix II); the part relative to medical workers is summarized in table 18. Since the data related to the distribution of doses among the film badges rather than among the people, it was not possible to calculate a value for Ω for individual groups. The highest collective doses were to workers in hospital x-ray departments and radium centres, who received 165 and 114 man rad, respectively. The highest annual average dose, 0.3 rad, was recorded at the radium centres. The total annual collective dose to all medical workers (excluding dentistry) was 355 man rad.

TABLE 17. SUMMARY OF OCCUPATIONAL DOSES TO MEDICAL AND ALLIED WORKERS IN CANADA FOR 1974

Occupational classification	*Annual collective dose (man rad)*	Ω	*Annual average dose (rad)*
Physician	81	1.1	0.05
Radiological technician (diagnostic)	398	0.5	0.06
Radiological technician (therapeutic)	49	1.1	0.14
Radiologist (diagnostic)	111	0.7	0.09
Radiologist (therapeutic)	24	1.3	0.19
Medical physicist	10	1.3	0.09
Laboratory technician	31	0.6	0.02
Isotope technician	56	1.0	0.15
Nurse	128	1.2	0.05
Ward aide or orderly	32	0.5	0.03
Gynaecologist	1	0.7	0.04
Dentist	37	0.3	0.01
Dental hygienist[a]	14	1.0	0.10
Chiropractor	11	0.4	0.02
Veterinarian	13	0.4	0.02
Other[a]	74	1.3	0.03

[a] Data for this classification do not fit well a log-normal.

TABLE 18. SUMMARY OF OCCUPATIONAL DOSES TO MEDICAL AND ALLIED WORKERS IN DENMARK FOR 1974 (EXCLUDING TWO ESTABLISHMENTS)

Category	*Number of departments*	*Annual collective dose (man rad)*	*Annual average dose (rad)*
X-ray departments (hospitals)	127	165	0.07
Surgical departments (hospitals)	14	8	0.04
Other departments (hospitals)	11	7	0.05
Hospitals in Greenland	19	1	0.01
Medical practitioners	21	3	0.03
Lung clinics	40	7	0.03
Isotope laboratories	122	30	0.02
Radium centres	21	114	0.29
Dermatologists	30	15	0.14
Chiropractors	63	0	0.00
Public dental clinics	10	1	0.01
Veterinary x-ray personnel	72	2	0.02

92. A general survey of doses in the personnel monitoring service provided by the SCPRI in France has been received by the Committee (88). The complete data are shown in tables 67 and 68 (appendix II). It should be noted that a reading of less than 10 mrad is recorded as zero (98). A summary of the medical doses for 1975 is given in table 19. From these results for 20 000 workers, it can be seen that the major part of the collective dose is due to radiodiagnosis. The annual average dose attributable to all radiodiagnostic practices (including dentistry) is of the order of 0.13 rad. All the establishments practising radiodiagnosis or radiotherapy in France were not included in the survey; an extended survey of 32 000 workers in 1973 is mentioned as giving almost the same overall annual average dose, although it contained a higher proportion of industrial workers (98). The Ω values for most groups are below 1.0; only four groups have a value appreciably greater than 1.0, showing that some high doses, due generally to isolated incidents, can make an excessive contribution to the collective dose when the great majority of individual doses are low. Some data were also supplied on internal doses from tritium to French medical workers (88). Annual average doses from 1968 to 1976 were all less than 0.02 rad, and no annual doses exceeding 1.5 rad were recorded. The data are shown in table 69 (appendix II).

TABLE 19. SUMMARY OF OCCUPATIONAL DOSES TO 20 517 MEDICAL WORKERS IN FRANCE, 1975

Type of establishment	*Number of workers*	*Annual collective dose (man rad)*	*Ω*	*Annual average dose (rad)*
Radiodiagnostic				
Hospitals	6 787	1 220	0.9	0.18
Private specialized medicine, clinics	1 378	300	0.8	0.22
Private radiology	1 101	240	1.4	0.22
Private general medicine	625	90	1.0	0.15
Industrial medicine, dispensaries	4 194	210	0.6	0.05
Dental surgeries, stomatology	2 661	110	0.2	0.04
Total	16 746	2 170	0.8	0.13
Radiotherapeutic				
Conventional	713	260	0.7	0.36
Curie	484	100	1.3	0.20
Cobalt	797	130	1.2	0.17
High-energy	456	60	0.5	0.14
Nuclear medicine	1 321	210	0.2	0.16

93. The total number of persons in New Zealand whose exposures are monitored are shown in table 70 (appendix II) (127). The largest numbers are engaged in medical work, principally diagnostic radiology, dentistry and therapy. There are in addition other users, but when these have been monitored the doses have been found to be consistently low. The annual average dose for all categories of users was estimated to be 0.11 rad. This leads to an annual collective dose from human medical procedures of about 300 man rad. For certain categories, notably medical diagnosis and therapy, the mean doses are greater than 0.1 rad.

94. As part of an exercise to establish lifetime doses, a considerable amount of data have been received from Australia (106). These data on medical and allied workers are shown in table 20. All the annual average doses are well below 0.5 rad, with many groups less than 0.1 rad. For workers occupied in medical and dental procedures including radiology, dermatology and nuclear medicine, the weighted mean annual dose for the samples tabulated is 0.11 rad; multiplying this value by the number of Australian workers in these occupations (table 1) gives an annual collective dose of 1400 man rad.

95. Some information on dose to workers with x rays and isotopes has been received from South Africa (9). These data are summarized in table 21. The parameters were derived by a log-normal fit to the dose distribution.

96. A breakdown of annual doses in 1974 according to occupation has been provided by Switzerland (30). These are shown in table 71 (appendix II), and the doses relevant to medical work are summarized in table 22.

97. Data from Thailand are shown in table 63 (appendix II) (94). The annual collective doses in 1974 due to radiography, radium use and nuclear medicine were 200, 77 and 69 man rad, respectively. The highest annual average dose was 0.46 rad, to radium workers.

98. Annual average doses have been supplied for persons employed in the medical field in West Berlin, and in the states of Niedersachsen, Hamburg, and Schleswig-Holstein in the Federal Republic of Germany from 1969 to 1974. The data are shown in table 74 (appendix II) (10a). The mean values were not determined by the Committee from a log-normal plot, but were reported to have been calculated by arithmetical mean value formation, omitting the two extreme ends of the dose distribution. The mean values are quoted separately for workers with radioactive substances and radiation, and workers with x rays only. The fluctuation of the average with time and place is considerable; however, a tendency to decrease over the years can be observed. The mean values for workers with x rays are lower than for those workers using radioactivity and radiation.

99. A very comprehensive set of information on occupational doses in the German Democratic Republic is available for the years 1970-1972 (65, 66, 67). Some of these data are shown in table 72 (a, b and c) in appendix II. A typical analysis of the doses to medical workers in 1972 is shown in table 23.

B. INDUSTRIAL USES OF RADIATION AND RADIOACTIVITY

100. Very few countries provided comprehensive summaries or estimates of doses due to all industrial uses of radiation or radioactivity. It is generally recognized that industrial radiography gives rise to some of the highest average individual doses and to a large proportion of the overexposures. This particular occupational group and some others are covered in more detail in chapter VII.

TABLE 20. AVERAGE OCCUPATIONAL DOSES TO MEDICAL AND ALLIED WORKERS IN AUSTRALIA

Occupational classification	*Number of workers in sample*		*Annual average dose (rad)*	*Fraction of dose from sealed gamma sources*[a] *(%)*
	Male	*Female*		
Radiology				
Hospital radiologists, including trainees and medical practitioners	184	15	0.16	
Radiologists in clinics and private practices	59	1	0.31	
Radiographers, hospital and private practices	500	633	0.14	
Assistants, nurses, porters etc.	53	359	0.09	
Dermatology, gynaecology and radiotherapy				
Dermatologists	19	–	0.10	30
Assistants, including therapy radiographers	–	9	0.18	70
Radiotherapists and gynaecologists including trainees	29	7	0.16	90
Therapy radiographers, physicists	57	94	0.10	80
Assistants	16	37	0.08	90
Nurses of patients with sealed sources *in situ*	1	228	0.44	100
Nuclear medicine				
Nuclear radiographers and assistants, including trainees	247	234	0.08	35
Dentistry				
Dentists	343	74	0.01	
Dental nurses and assistants	66	505	0.01	
Chiropractic				
Chiropractors	96	7	0.03	
Veterinary				
Veterinary surgeons	111	16	0.02	
Assistants	16	89	0.01	

[a] Except for last entry, which pertains to gamma sources of energy >160 keV.

TABLE 21. OCCUPATIONAL DOSES TO X-RAY WORKERS AND ISOTOPE USERS IN SOUTH AFRICA, 1974

Category	*Number of workers*	*Annual collective dose (man rad)*	*Ω*	*Annual average dose (rad)*
X-ray workers	5 090	336	0.6	0.07
Isotope users	1 832	167	0.8	0.09

TABLE 22. OCCUPATIONAL DOSE TO MEDICAL WORKERS IN SWITZERLAND, 1974

Type of establishment	*Annual collective dose (man rad)*	*Ω*	*Annual average dose (rad)*
Hospital	249	1.0	0.14
Clinic	35	1.4	0.05
Medical private practice	132	1.0	0.05
Dental private practice	284	0.5	0.09
Chiropractic	1	–	0.02
Other	36	0.3	0.04

TABLE 23. OCCUPATIONAL DOSES TO MEDICAL WORKERS IN THE GERMAN DEMOCRATIC REPUBLIC, 1972

Category	*Number of workers*	*Annual average dose (rad)*	*Ω*	*Annual collective dose (man rad)*
X ray	17 028	0.02	0.9	331
Brachytherapy	551	0.54	1.5	298
Radionuclides (excluding brachytherapy)	440	0.20	0.4	86
Accelerator	13	0.02[a]	0	0.3[a]
Deep therapy	132	0.42	2.7	55
Total	18 164	0.06	0.7	1 131

[a] Estimated by comparison of the distribution with x-ray workers, since there were insufficient data to fit a log-normal distribution.

101. For the United Kingdom, it has been estimated (109) that there are approximately 18 000 industrial workers occupationally exposed to radiation, of whom 7000 are industrial radiographers (5). The annual dose distribution is available for a sample of approximately

10 per cent of these 18 000 workers (81, 109); it is given in table 73 (appendix II). It was noted, however, that the proportion of industrial radiographers in the sample was probably less than the overall proportion. With this reservation, the annual average dose to industrial workers in the United Kingdom can be estimated from figure XIV, which is a log-probability plot of the data, as 0.43 rad, and the annual collective dose to all 18 000 workers as 7700 man rad, with value for Ω of 1.1.

102. Log-probability plots of the data for all categories of United States Atomic Energy Commission and agreement state licensees are shown in figures XV and XVI (64). Curve A in figure XV represents the data for those licensees who report (62 090 individuals), and Curve B (155 090 individuals) includes the estimated number who do not report, assuming that the annual doses are less than 2 rad. Good agreement with a log-normal distribution is obtained for these large samples. Log-probability plots of the annual dose to two categories of United States Atomic Energy Commission licensees are shown in figures XVII and XVIII (16). Figure XVII shows the results for by-product material licensees in manufacturing and distribution from 1971 to 1974 and figure XVIII, for industrial radiographers over the same period. Those included were the licensees who reported all monitored personnel, not only those receiving annual doses greater than 1.25 rad. Since this is only a partial sample, no analysis has been performed on the values, but Brodsky estimated that the data fitted a log-normal distribution up to annual doses of 1 rad (16). Klement *et al.* (64) estimated the doses to the reporting United States Atomic Energy Commission licensees and agreement state licensees shown in table 24 for 1969/70. If these are added, the total annual collective dose from industry, radiography and "unspecified" is estimated as 5925 man rad delivered at an average dose of 0.19 rad. More recent estimates for 1974 have been made by the United States Nuclear Regulatory Commission (18). The dose distributions for the two categories of covered licensees, industrial radiography and manufacturing and distribution are shown in table 75 (appendix II).

TABLE 24. SUMMARY OF ESTIMATED DOSES TO INDUSTRIAL WORKERS IN THE UNITED STATES, 1969/70

Category	*Number of workers*	*Annual collective dose (man rad)*	*Annual average dose (rad)*
Reporting Atomic Energy Commission licensees			
Industrial	13 331	2 140	0.16
Radiography	1 894	752	0.40
Not specified	7 815	1 020	0.13
Reporting agreement state licensees			
Industrial	6 479	1 490	0.23
Radiography	1 174	294	0.25
Not specified	731	226	0.31
Total	31 424	5 920	0.19

103. Some information has been supplied on average doses to industrial workers in Australia (106); it is summarized in table 25. The average doses are in all cases rather low, even for the group which included industrial radiographers.

104. A considerable body of data has been supplied from Canada (4) on doses to non-medical industrial workers. The dose distributions have been fitted by log-normal distributions and the resultant parameters are shown in table 26.

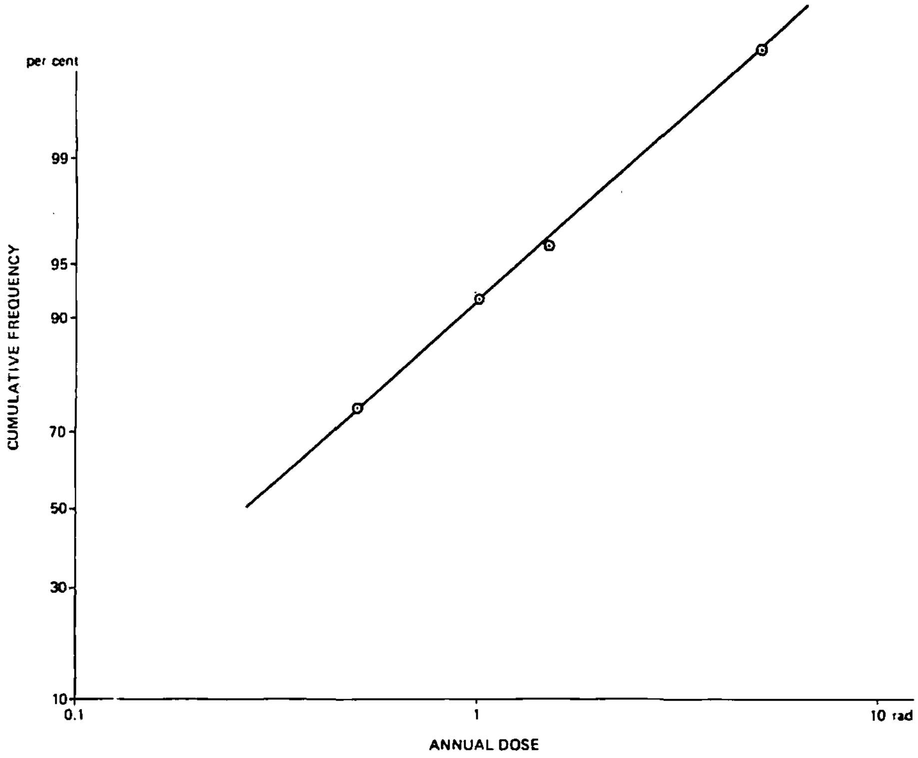

Figure XIV. Log-probability plot of the annual doses to a sample of industrial workers in the United Kingdom, 1974

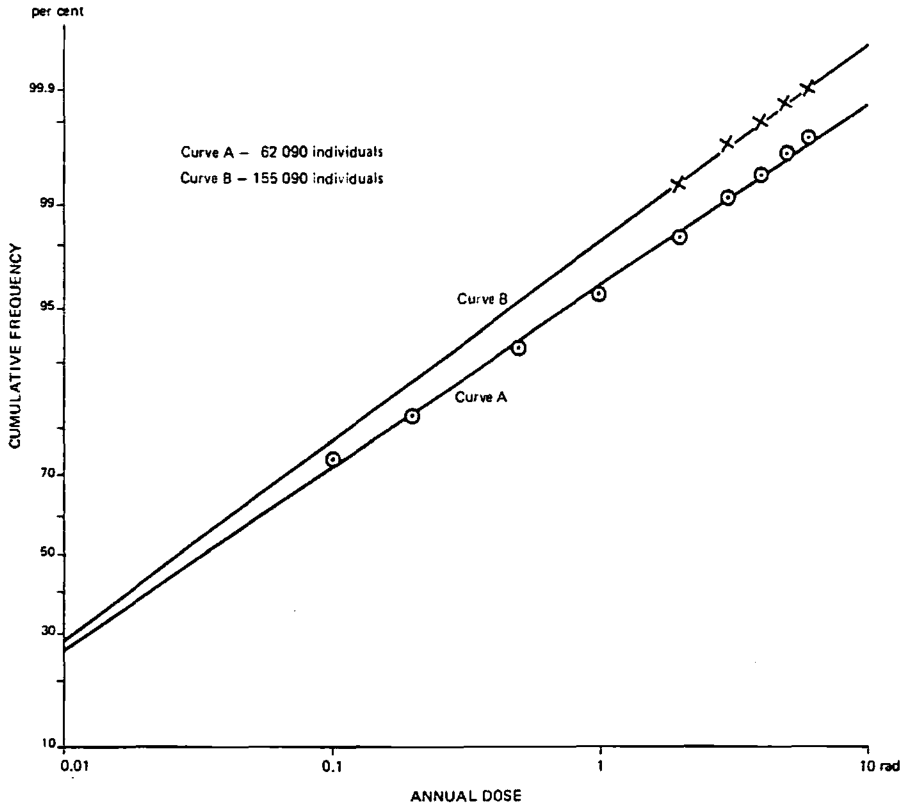

Figure XV. Log-probability plot of annual doses to radiation workers employed by United States Atomic Energy Commission licensees, 1969

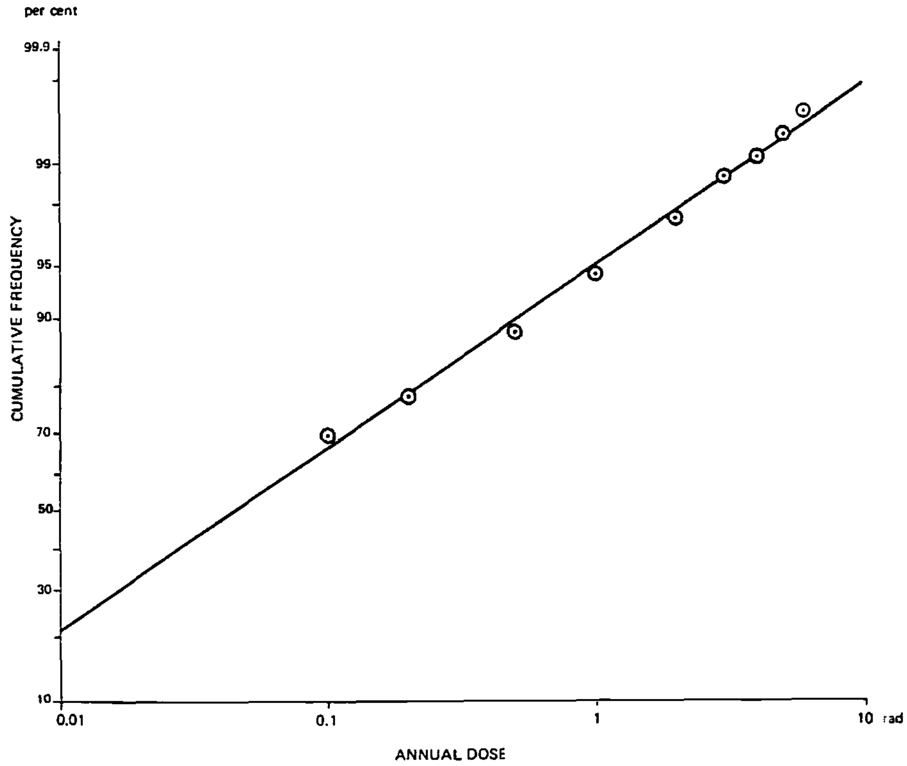

Figure XVI. Log-probability plot of annual doses to radiation workers employed by United States agreement state licensees, 1969

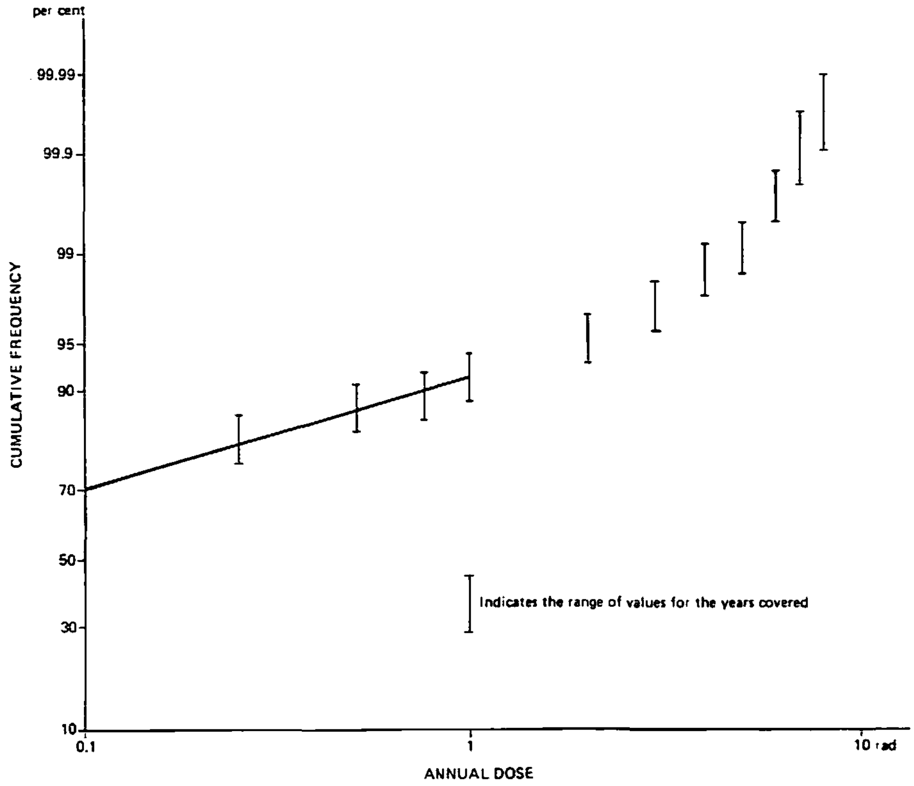

Figure XVII. Log-probability plot of annual doses to by-product licensees in manufacturing or distribution, United States, 1971-1974

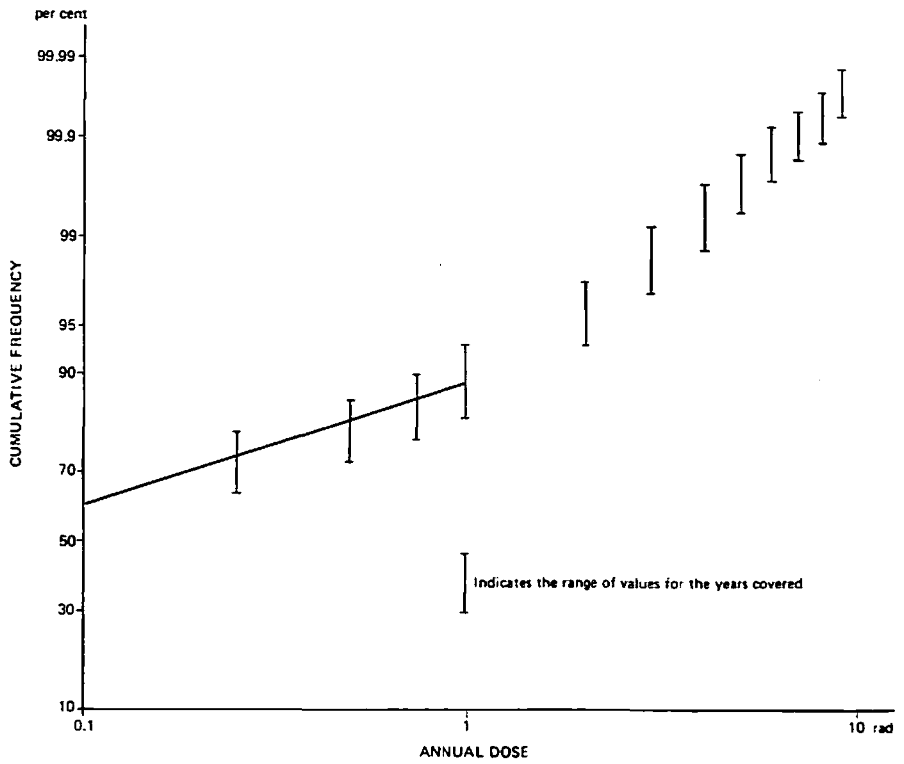

Figure XVIII. Log-probability plot of annual doses to industrial radiographers, United States, 1971-1974

TABLE 25. AVERAGE OCCUPATIONAL DOSES TO INDUSTRIAL AND RESEARCH WORKERS IN AUSTRALIA

Occupational classification	*Number of workers in the sample*		*Annual average dose (rad)*	*Fraction of dose from specified sources (%)*
	Male	*Female*		
Research				
Users of x-ray analysis units, electron microscopes, etc.	341	26	0.01	
Industry				
Users of enclosed installations[a] or "quality control" sources, e.g., package monitors, thickness gauges etc.	341	92	0.01	
Users of open installations,[a] including industrial radiographers	413	12	0.24	Sealed gamma >160 keV, 80
Users of tracers	265	85	0.06	Gamma >160 keV, 95
Installation and maintenance engineers	147	–	0.02	

[a] As defined in ICRP Publication 15 (52a).

TABLE 26. SUMMARY OF OCCUPATIONAL DOSES TO INDUSTRIAL WORKERS IN CANADA, 1974

Occupational classification	*Annual collective dose (man rad)*	*Ω*	*Annual average dose (rad)*
Dial painter[a]	4	2.8	0.40
Instructor	1	0.2	0.01
Instrument technician	62	2.1	0.10
Laboratory technician	97	1.9	0.07
Oil logger	14	1.5	0.09
Radiography	369	2.0	0.43
Scientist and engineer (field)	61	2.0	0.17
Scientist and engineer (laboratory)	26	1.2	0.02
Other technician[a]	1 230		0.53
Office staff[a]	24	1.8	0.02

[a] Data for this classification did not fit well a log-normal.

TABLE 27. SUMMARY OF OCCUPATIONAL DOSES TO INDUSTRIAL WORKERS IN DENMARK, 1974

Type of establishment	*Number of departments*	*Annual collective dose (man rad)*	*Annual average dose (rad)*
Industrial x-ray and gamma	44	26	0.11
X-ray firm	15	14	0.07
X-ray analysis	30	1	0.00

TABLE 28. SUMMARY OF DOSES TO INDUSTRIAL WORKERS IN THE GERMAN DEMOCRATIC REPUBLIC, 1970-1972

Year	*Category*	*Number of workers*	*Annual average dose (rad)*	*Ω*	*Annual collective dose (man rad)*
1970	X-ray	1 725	0.03	1.1	57
	Radionuclide	1 697	0.08	1.0	128
1971	X-ray	1 790	0.02[a]	0.0	36[a]
	Radionuclide	1 864	0.05	1.4	102
1972	X-ray	1 619	0.03	0.7	48
	Radionuclide	1 740	0.08	0.5	131

[a] Mean dose estimated by comparison with other years, since there were insufficient data to fit a log-normal distribution.

TABLE 29. SUMMARY OF OCCUPATIONAL DOSES TO 2579 INDUSTRIAL AND RESEARCH WORKERS IN FRANCE, 1975

Type of work	*Number of workers*	*Annual collective dose (man rad)*	*Ω*	*Annual average dose (rad)*
Industrial radiography (x and gamma)	839	33	0.3	0.04
Research and industrial application of unsealed sources	752	26	0.4	0.03
Other non-medical	988	86	1.6	0.09

105. Some information on industrial workers in Denmark is included in table 66 (appendix II). The results are summarized in table 27 (118).

106. The data supplied on the German Democratic Republic and shown in table 72 (a, b and c) in appendix II includes some information on doses to industrial workers. These workers are divided into those using x rays and those using radionuclides, with a small number using accelerators. None of those using accelerators received annual doses exceeding 0.5 rad in the years 1970-1972. The results for the other workers are summarized in table 28 (65, 66, 67).

107. Information on occupational doses in France has been provided by SCPRI (88), and is given in tables 67 and 68 (appendix II). A summary is given in table 29. The average doses and Ω values are low; this is true both for radiography installations and for work with unsealed sources. In general, industrial and research workers do not incur high doses and the low Ω values demonstrate the rarity of incidence. For all other non-medical

applications (e.g., crystallography, neutron sources, particle accelerators) the average dose is also low but with a relatively higher Ω value because of a small number of incidents.

108. Information on the doses to radiography workers using x rays and gamma sources has also been supplied by Hungary (15). The data are summarized in table 76 (appendix II). Log-probability analysis shows annual average doses of 0.35 rad for gamma radiographers and only 0.06 rad for the x radiographers. The Ω value of the distributions were 1.9 for gamma radiographers and 1.3 for x radiographers. The annual collective dose from all radiography was 480 man rad.

109. A summary of doses to industrial workers in Switzerland in 1974 is included in table 71 (appendix II) (30). The annual average dose is given as 0.23 rad, with an annual collective dose of 60 man rad. The Ω value is 0.6. A more detailed set of data for 1969-1975 is shown in table 77 (appendix II) (60, 61). Typical annual collective doses in recent years are about 100 man rad at an Ω value of 0.1-0.3.

110. Data are available for the states of Niedersachsen, Hamburg and Schleswig-Holstein in the Federal Republic of Germany, and for West Berlin for the years 1969 to 1974. They are shown in table 74 (appendix II) (10a). The reported average dose values are mean values which were determined from the dose distribution by arithmetical mean value formation, omitting the two extreme ends of the dose distribution. The mean values refer to all technical applications of radioactivity and radiation, including the nuclear industry. The doses are quoted separately for workers with radioactivity and radiation and for workers with x rays only. For the medical field, as was noted in paragraph 98, the doses show considerable fluctuations with time and place; the average dose values to workers from x rays are nearly always lower than those to workers from radiation sources.

C. USES OF RADIATION AND RADIO-ACTIVITY BY MILITARY PERSONNEL

111. The majority of involvement with radiation and radioactivity by military personnel is concerned with the same activities as civilian personnel: operation and maintenance of nuclear reactors, medical treatment and procedures, radiography etc. It is of interest to compare the doses to these categories of military workers with the doses to their civilian equivalents, where they can be made available.

112. Klement *et al.* (64) give data from the United States for different occupational groups. The distribution of doses varies with the group. Although in all cases the majority of workers receive low doses, the percentage receiving very low doses is higher for the army and air force personnel. Log-probability plots of these data for the army and the air force are shown in figures XIX and XX, in which the lines are the result of least-squares fitting to the data points. The number of workers who might be exposed to ionizing radiation is high, 22 790 and 34 975 for the army and air force, respectively, but the number of workers receiving annual doses more than 100 mrad is given as 298 and 330 in the

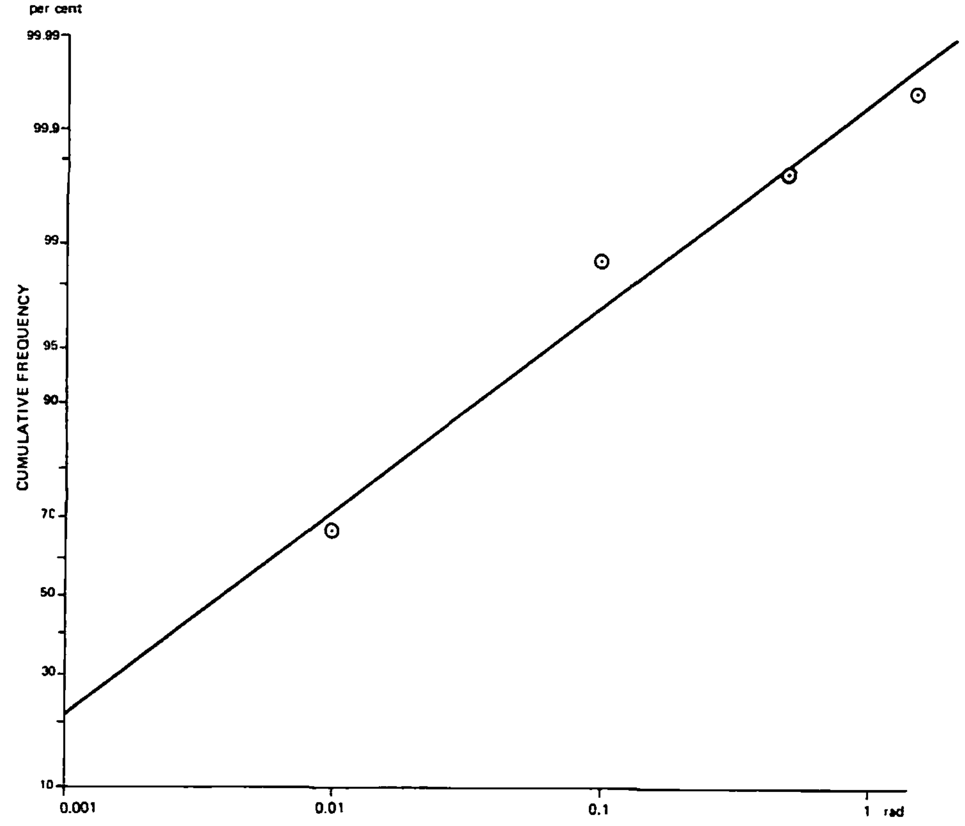

Figure XIX. Log-probability plot of annual doses to radiation workers in the United States Army, 1969-1970

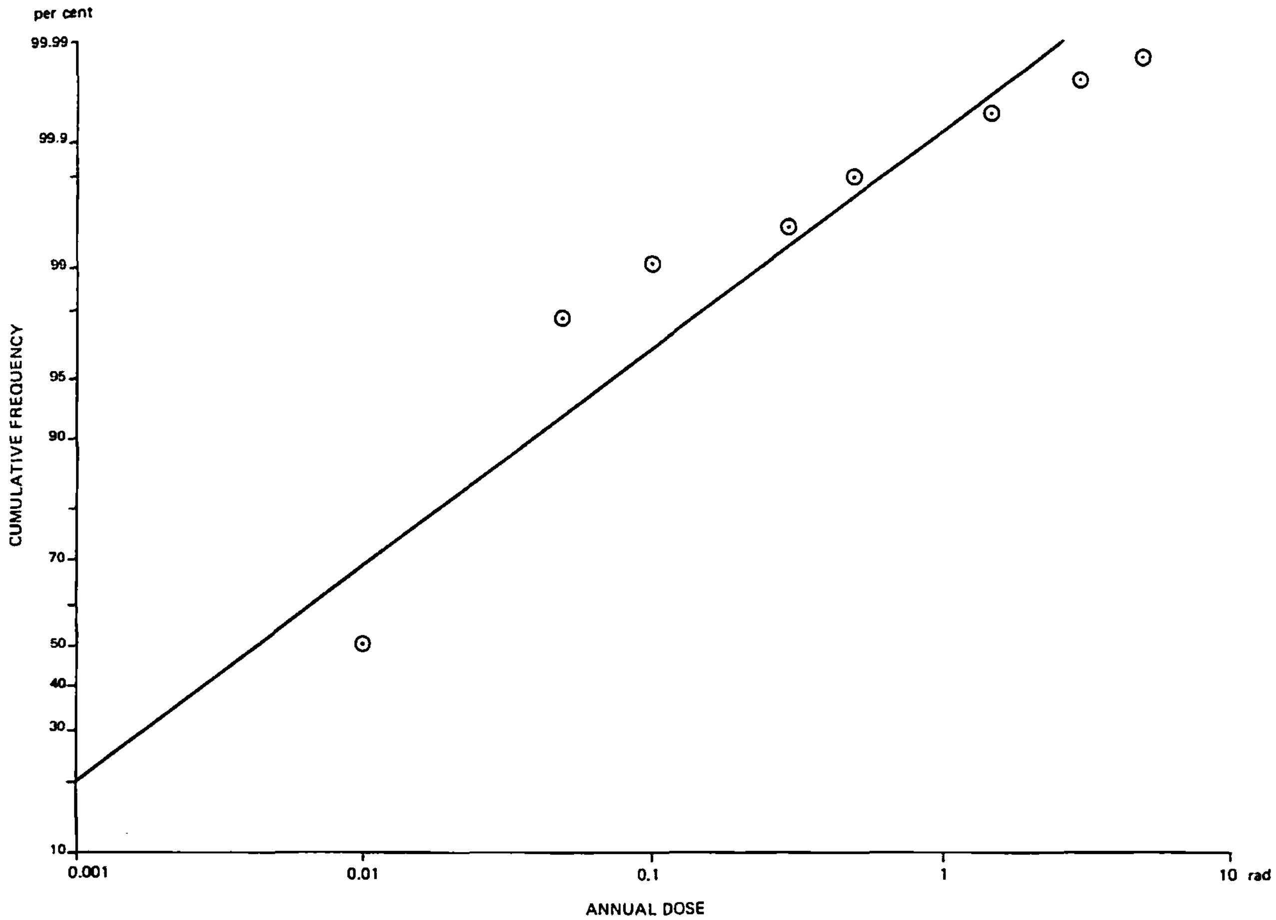

Figure XX. Log-probability plot of annual doses to radiation workers in the United States Air Force, 1969-1970

original data and is estimated as 296 and 329 from the log-normal plot. The values of the annual average dose, as estimated from the log-normal plots, are 15 and 18 mrad for the army and air force, respectively, compared with the published values of 100 and 88 mrad, but these published values were calculated for those workers receiving annual doses above 10 mrad.

113. The collective dose can be estimated from both sets of data, using either the total number of workers and the average dose as obtained from the log-probability plot, or the number of workers receiving annual doses over 10 mrad and the published annual average dose. The collective doses calculated from the log-probability plots are 360 and 650 man rad for the army and air force respectively, whereas those calculated using the published average doses are 740 and 1550 man rad. The discrepancy of a factor of about two for the collective dose is due to the different methods of including the large number of low doses. The extrapolation of the log-probability plot assumes a log-normal distribution of doses, whereas the other method probably assigns a nominal dose value to the low-dose group; it is not clear from the text whether this assignment was actually made.

114. In the United Kingdom Ministry of Defence, radiation dose records are analysed to obtain the number of films received from each establishment and a breakdown of the distribution of readings as a function of occupation (95). The distribution is reduced to two blocks, those films reading 0.025 rad or less and those reading greater than 0.025 rad. The overall average dose is then calculated using individual results above 0.025 rad and an estimate of the average below 0.025 assuming that the results follow an exponential distribution (95). The results for 1971-1974 are shown in table 30.

TABLE 30. ANNUAL AVERAGE DOSE BY OCCUPATIONAL GROUP FOR WORKERS IN THE UNITED KINGDOM MINISTRY OF DEFENCE, 1971-1974

(rad)

Occupational group	*1971*	*1972*	*1973*	*1974*
Supervisors	0.58	0.47	0.21	0.20
Medical	0.22	0.21	0.10	0.21
Dental	0.15	0.16	0.17	0.16
Industrial	0.46	0.59	0.62	0.50
Laboratory	0.15	0.14	0.14	0.18
Operators	0.33	0.31	0.36	0.48
Instructors	0.11	0.12	0.16	0.17
Students	0.37	0.40	0.45	0.41
Health physics	0.13	1.33	0.76	0.94
Procurement executive	0.24	0.20	0.21	0.19
Other	0.58	0.55	0.45	0.53

D. NON-URANIUM MINING

115. The doses to uranium miners have been considered in paragraphs 45-49. Radon also occurs in relatively high concentrations in many non-uranium mines. An excess

TABLE 31. DISTRIBUTION OF RADON-DAUGHTER EXPOSURE IN NON-URANIUM MINES IN VARIOUS COUNTRIES

Country		Year	*Radon-daughter concentration range (WL)*					*Weighted average annual exposure*[a] *(WLM)*
			< 0.1	*0.1-0.3*	*0.3-1.0*	*> 1.0*	*All*	
			(Number and, in parentheses, percentage of miners or mines)					
Finland	Miners	1973	469 (35)	246 (18)	247 (19)	369 (28)	1 331	8.8
		1974	898 (68)	310 (23)	119 (9)	0	1 327	1.7
	Mines	1973	8 (36)	4 (18)	4 (18)	6 (28)	22	
		1974	13 (65)	5 (25)	2 (10)	0	20	
Italy	Mines	1973	8 (50)	4 (25)	4 (25)	0	16	–
Norway	Miners	1972	1 608 (86)	264 (14)	0	0	1 872	0.9
	Mines	1972	20 (83)	4 (17)	0	0	24	
South Africa	Miners	1973	227 000 (71)	69 000 (21)	21 000 (7)	3 000 (1)	320 000	1.7
Sweden	Miners	1970	1 110 (22)	1 560 (33)	2 000 (42)	130 (3)	4 800	4.8
		1974	1 860 (40)	2 390 (52)	360 (8)	0	4 610	2.1
		1976	2 730 (51)	2 345 (44)	225 (4)	0	5 300	1.7
	Mines	1970	25 (45)	8 (15)	18 (33)	4 (7)	55	
		1974	28 (56)	14 (28)	8 (16)	0	50	
		1976	29 (63)	12 (26)	5 (11)	0	46	
United Kingdom	Miners	1973	1 073 (60)	49 (3)	223 (12)	443 (25)	1 788	4.2
		1975						3.4
	Mines	1973	25 (61)	3 (7)	9 (22)	4 (10)	41	

[a] The weighted average annual exposures are calculated by multiplying the number of miners in each group by the mean values of the radon concentration (0.05, 0.2, 0.65 or 2 WL) and by 12 months, obtaining the sum of the products and dividing by the total number of miners. See paragraph 116 for treatment of British data.

of lung cancer has been found among some non-uranium miners in a number of countries (14, 87, 92, 119), and the excess has been attributed to radon-daughter exposure (100).

116. The number of miners and mines in different concentration categories are presented in table 31 for six countries (10, 13, 59, 79, 101, 108). The corresponding weighted annual exposure is also presented for each country. The United Kingdom miners included in table 31 represent 70 per cent of all non-coal miners, and the United Kingdom mines, mostly metalliferous, represent 41 per cent of all non-coal mines. The annual exposure is calculated directly from the original data (108). For comparison, the annual exposure would be calculated as 7 WLM using the same method as for the other entries in the table. The data from Finland are based on the maximum values of radon-daughter concentration in working areas (59). The sixteen Italian mines were selected by Bottino *et al.* (13) to give a general picture of the situation. The radon-daughter concentrations have been calculated by multiplying the radon concentrations by 0.2, which was the average equilibrium factor (13). In the conversion of the Norwegian values an average equilibrium factor of 0.6 was used (79). Since the temporal variations in radon and daughter concentrations can be considerable, and since measurements tend to be relatively infrequent, the data in table 31 should be treated with caution. Nevertheless, it is clear that some miners are exposed to more than 4 WLM in a year. This value or its equivalent has been adopted by several national authorities as the occupational exposure limit for miners. The results that a determined programme of corrective action can achieve in a relatively few years can be seen, for example, from the Swedish data in table 31.

VII. DOSES TO SPECIFIC OCCUPATIONAL GROUPS

117. It is the intention in this chapter to review selected occupational groups which appear to be of special interest because they fall well outside the anticipated dose distribution defined in chapter III as the reference distribution. The characteristics used to define whether any particular occupational group receives doses that are consistent with the reference distribution are the average annual dose $\bar{D}$ and the relative proportion Ω of the annual collective dose due to annual doses exceeding 1.5 rad. For the reference distribution, $\bar{D} = 0.5$ rad and $\Omega = 1$. In selecting a range of values for $\bar{D}$ and Ω which appear appropriate for judging actual distributions, note is taken of the actual and theoretical extremes of the two parameters. In principle, $\bar{D}$ has a range from zero to a very large number, but in practice it has a range from almost zero to a few rads. It appears that a suitable criterion for selecting distributions for study may be that $\bar{D}$ is outside the range 0.1-1.0 rad. The theoretical range of Ω is from zero to 3.23, and in practice values from zero to nearly 3.0 are found. It therefore appears that a suitable range of values for this parameter outside which the distribution is unusual is 0.1-2.0. There will, of course, be a dependence on country and year, so that the assignment to a particular category is not definite, but merely indicative.

A. GROUPS FOR WHICH $\bar{D} \geqslant 1.0$ rad OR $\Omega \geqslant 2.0$

1. Industrial radiographers

118. This is an occupation in which large sources capable of giving substantial doses in a short time are used, usually under adverse conditions, with a minimum of direct radiation protection control. An extensive survey of doses to industrial radiographers was carried out in the United Kingdom (6). Tables 78 and 79 (appendix II) show the quarterly doses for a sample of individual firms concerned mainly with factory and site radiography. It is not possible to calculate annual average doses from these data, but it appears likely that $\bar{D} > 1$ rad, for site radiographers at least. No correlation with size of firm is apparent, but site radiographers, in general, received higher doses than factory radiographers, probably because of adverse working conditions or lack of direct supervision. The United Kingdom study was initiated as a result of a number of workers receiving excess radiation doses. Table 80 (appendix II) summarizes these occurrences of excess dosage for a number of years (121). This experience is reflected in other countries; for example, analysis of the more significant radiation exposure incidents occurring among United States Atomic Energy Commission contractors and licensees in the United States during 1971 shows that of 14 incidents, 8 involved industrial radiographers (111). Many other incidents of overexposure involving industrial radiographers have been reported (20, 40, 57, 74, 75, 96).

119. On the other hand, although the United States has experienced a substantial number of incidents of overexposures involving radiographers, table 75 (appendix II) shows that the average doses and the Ω value are well within the normal range (18). The same is true for the Canadian radiographers represented in table 26 (4), which displays values very similar to those in the United States.

120. Average doses to industrial x-ray workers and gamma-ray workers in Denmark are comparatively low, as shown in table 27. Information from the German Democratic Republic and Hungary, already noted in paragraphs 106 and 108, tends to show a considerable difference between x radiography and gamma radiography with radionuclide sources, with the highest average doses being received by gamma radiographers. This difference could also be the reason for the difference between the average doses received by site and factory radiographers in the United Kingdom, assuming that site radiographers were more likely to use radionuclide sources.

121. It appears that industrial radiographers, particularly those using gamma-ray rather than x-ray sources, may still be among the highest exposed groups with a particular tendency to incidents involving overexposure.

2. Luminizers

122. Luminizers have traditionally been among the workers receiving higher-than-average doses. The marked improvement which could be brought about by an energetic programme of radiation protection was demonstrated in the 1972 report. Mean annual doses to tritium luminizers in 1969-1970 were around 0.5 rad in France, the Federal Republic of Germany and the United Kingdom (omitting two highly exposed individuals). Data have been supplied (46) for workers producing luminous paint and gaseous tritium light sources in the United Kingdom, who are regularly monitored for tritium in urine. The results for 1974 are shown in table 81 (appendix II). The first group of workers provided no samples above the derived investigation level (DIL), which corresponds to a committed dose[1] of 0.050 rad in two weeks; the doses to this group were therefore not recorded. The second group provided some samples below the DIL which are not included in the value for the committed dose. The collective dose was re-estimated, taking this into account, as 115 man rad. In addition, there were 87 luminizers who were not monitored regularly; an estimate was made of the contribution of these luminizers to the collective dose, which resulted in an overall estimate of 157 man rad for the annual collective dose to the 223 luminizers, corresponding to an annual average dose of 0.7 rad. Using these figures with the data from table 81 (appendix II), the Ω value can be estimated as 1.2.

123. A detailed breakdown of annual doses for 1969-1975 is available for Switzerland. These data are shown in table 82 (appendix II) and summarized in table 32 (60, 61). A similar set of data for French luminizers over essentially the same period is shown in table 83 (appendix II) and summarized in table 33 (88). Possibly because of the small number of workers in France, many of these dose distributions were not a good fit to a log-normal curve, whereas the Swiss data in general were. Values for Ω for the Swiss data were therefore estimated using a log-probability plot, but those for the French data were obtained directly from the numbers in each dose range. Both sets of data show the same improvement over the years, in terms of the values for Ω. A similar downward trend in annual average dose is apparent in the Swiss data but not the French; all of the annual average doses to French luminizers are, however, less than 1 rad, the recent average for Swiss luminizers.

124. Doses to dial painters in Canada are summarized in table 26 (4). The high Ω value may be due to the small

TABLE 32. DOSES TO TRITIUM LUMINIZERS IN SWITZERLAND, 1969-1975

Year	*Number of workers monitored*	*Annual collective dose (man rad)*	*Annual average dose (rad)*	Ω
1969	333	618	1.85	2.5
1970	313	478	1.53	1.9
1971	226	276	1.22	2.0
1972	228	268	1.18	2.0
1973	221	231	1.05	1.7
1974	290	316	1.09	1.8
1975	235	239	1.02	1.7

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[1] The term "committed dose" is used here to mean the time-integral of the dose rate in an individual over his lifetime from an intake of radioactivity during a specified period of time.

TABLE 33. DOSES TO TRITIUM LUMINIZERS IN FRANCE, 1968-1975

Year	*Number of workers monitored*	*Annual collective dose (man rad)*	*Annual average dose (rad)*	Ω
1968	30	16	0.52	3.0
1969	24	11	0.47	2.3
1970	15	13	0.86	2.8
1971	35	6	0.17	0
1972	33	10	0.29	1.8
1973	67	44	0.66	1.7
1974	84	46	0.55	1.6
1975	90	44	0.49	1.5

number of workers involved (only 11). All of the contribution to the collective dose from annual doses above 1.5 rad is due to one individual who received 3.8 rad in the year.

125. Some information on monitoring of luminizing workers exposed to ^{147}Pm in the German Democratic Republic has been reported (3). The maximum annual dose was estimated from excretion monitoring to be 6 rad, to either the lung or gastro-intestinal tract, but the annual doses to these organs were in the range 1-3 rad for the 10 other individuals with measurable ^{147}Pm levels.

126. In view of the increasing use of tritium in the watch industry, supervision of workers using tritium in the Federal Republic of Germany has continued. Table 84 (appendix II) shows the mean annual dose per person from 1966 to 1975 (19). When the values are broken down into specified ranges, it can be seen that in different years, 40-70 per cent of workers received doses exceeding 0.1 rad, and 5-40 per cent received doses in the range 1.5-5 rem. While in the 1960s up to 13 per cent of the workers received doses exceeding 5 rad, no such doses were recorded from 1970 to 1972. In 1973-1975, one or two workers received annual doses in excess of 5 rad. The average annual dose has varied from 0.4 to 1.4 rad.

127. Luminizing is an occupation in which high doses can be received by a few individuals, but improvements in the practice of radiological supervision over the last decade have resulted in the achievement of an adequate level of protection.

3. Medical workers in radiotherapy

128. Undoubtedly the highest doses from the use of radiation in radiotherapy have been from the use of radium sources for interstitial and intracavitary therapy. This was illustrated in the 1972 report with data from the German Democratic Republic and Sweden. In recent years the trend has been to replace radium sources by other nuclides (35, 126). Conventional radium tubes and needles can be replaced directly with ^{137}Cs tubes and needles, which have the advantage, for radiation protection, of a lower gamma energy. In addition, "afterloading" techniques have been developed for both the treatment of cancer of the uterine cervix and interstitial radiotherapy. In these techniques, a hollow tube is positioned first and the source then introduced into the tube; the result is a reduction in the occupational dose.

129. A survey of techniques used in the treatment of cancer of the cervix was given by Snelling (99); ^{192}Ir, ^{137}Cs and ^{60}Co are used in various afterloading systems (22, 42, 58). Iridium-192 and ^{182}Ta wires are used in afterloading techniques in interstitial radiotherapy (86, 90).

130. From the German Democratic Republic, for example, the Committee has had data showing that in the mid-1960s the highest monthly doses and most overexposures were due to medical radium applications. From the mid-1960s to 1970, all sealed radium sources for medical purposes were replaced by other radionuclide sources; since then the number of overexposures has considerably decreased (97). The French results reported in table 19 show that interstitial and intracavitary therapy (Curie therapy) gave values for Ω slightly greater than 1.0, accompanied by low values of the annual average doses. This is explained by the new techniques using ^{192}Ir and ^{137}Cs in afterloading, causing hardly any exposure of the operators to radiation; however there still remain a small number of radium workers who are exposed to higher doses. The highest annual average doses for any medical workers in Denmark were for workers at radium centres. These were still low by comparison with most other countries, but not enough information was given to enable the Ω value to be calculated, so nothing can be deduced as to the reason. It is not clear from the Canadian results in table 17 which category would be expected to handle radium, but no categories had high values of either $\bar{D}$ or Ω.

131. The effect of the introduction of improved procedures and equipment on doses received in a single institution are exemplified in the results submitted by Bozoky (15) and shown in table 85 (appendix II). As is pointed out by Bozoky, although the reduction in annual dose is considerable, the reduction in the mean energy imparted (referred to as the integral dose), calculated on the basis of measurements at ten different parts of the body, is very much less. There is some doubt whether average dose is a valid measure of harm for a procedure in which the distribution of dose over the body is extremely non-uniform.

132. The use of external-beam therapy would be expected to result in much lower doses to workers compared with intracavitary and interstitial therapy. Provided that the treatment rooms are adequately shielded, the users of cobalt teletherapy sources might be expected to receive slightly higher doses than users of x-ray or electron-beam sources. The French results reported in table 19 show that indeed cobalt therapy gave a higher Ω value and average dose than high-energy therapy. However, the annual average dose from conventional radiotherapy with low-energy x rays was the highest reported in 1974. The comparable group in the Canadian data in table 17 is radiological technicians (therapeutic) with an Ω value of 1.0 and a low mean dose. The mean dose received by Australian therapy radiographers (table 20) is also low.

4. Workers at nuclear reactors

133. Most of the data reported in paragraphs 53-68 relate to the collective doses rather than the individual doses of workers at nuclear reactor sites. Some additional data have, however, been received on the annual dose to different occupational groups within the overall reactor staff. Doses at two United Kingdom reactors are shown in tables 86 and 87 (appendix II) (39, 85). The one group of workers consistently receiving the highest annual average doses at both reactors is the radiological protection workers. Operational workers at one station also received annual average doses exceeding 1 rad in two successive years, although in the latest year (1974) their average dose had been reduced to 0.8 rad.

134. Doses to three groups of workers in the Canadian Ontario Hydro nuclear power stations are shown in table 88 (appendix II) (125). The group receiving the highest annual dose is mechanical maintenance workers. Radiological protection workers are not specifically identified as, in general, all workers carry out their own radiological protection procedures. Annual average doses to all workers at some United States nuclear power stations are higher than 1 rad (see table 48 in appendix II). There is no indication of those groups receiving the highest doses, although it could be inferred that, as maintenance operations contribute most of the collective dose, maintenance workers probably receive the highest average doses. Radiological protection monitors would also be expected to be closely associated with maintenance work.

5. Nuclear fuel reprocessing workers

135. Information has been provided (48) on average doses to some selected groups of workers at Windscale in the United Kingdom. The detailed results for 1973-1975 are shown in table 89 (appendix II). It is apparent that, as with reactors, operations and maintenance workers receive the highest annual average doses. The average doses to these small groups of workers are among the highest reported to the Committee.

6. Manufacturers of radiopharmaceuticals and industrial sources

136. The only specific information on workers producing radiopharmaceuticals and industrial sources has been supplied by the United Kingdom (82). The Radiochemical Centre produces a variety of sealed and unsealed sources for use in industry and medicine. The distribution of annual dose is given in table 90 (appendix II). The average annual dose has decreased from 1.11 to 0.76 rad from 1972 to 1974, but the value for Ω in 1974 was 2.2, indicating that a substantial proportion of the workers received annual doses in excess of 1.5 rad.

7. Miners

137. The doses to workers in uranium, coal and metalliferous mines have been discussed in paragraphs 45-49 and 115-116. From these it can be seen that, even with the reservations on conversion of WLM to lung dose, many miners are exposed to radon-daughter concentrations considered excessive by some authorities. Improvements in ventilation are under way in many countries where this problem exists (52b). Such efforts should be vigorously pursued; as has been noted, significant improvements can result within relatively few years.

8. Aircrew and cabin staff of jet aircraft

138. The increase of cosmic-ray dose rate with altitude was discussed in the 1972 report and in chapter I, section A, of Annex B. At the normal cruising altitude of subsonic jet aircraft, about 10 000-12 000 m, the dose rate is in the range 0.15-0.35 mrad h^{-1}. This range includes the variation within the solar cycle and with latitude from 43°N to 50°N (84). Some components of the radiation field have a measured RBE considerably greater than unity, and it has been estimated that if a quality factor were to be assigned to the mixed field it would be of the order of 1.5. With this factor, the dose equivalent rates would be in the range 0.25-0.50 mrem h^{-1}. If the average crew member flies at this altitude for 1000 h per year, then the average annual dose equivalent received would be in the range 0.25-0.5 rem.

139. In the case of supersonic aircraft flying at altitudes of 20 000 m, the dose rate is appreciably greater than that in conventional jet aircraft, but the combination of the increase in dose rate with the reduction in travelling time means that the dose received in a given journey is of the same order, whichever type of aircraft is flown. It is not yet clear whether supersonic aircrew will fly the same number of hours as conventional aircrew. If they do, the annual dose equivalent that they will receive could be in the range 0.5-1.5 rem. The provision of in-flight radiation dose-rate monitors to provide direct warning of solar flares will prevent the occurrence of large doses, and it is expected that the average dose equivalent from solar flares will be a small proportion of the total.

B. GROUPS FOR WHICH 0.1 rad $<\bar{D}<$ 1.0 rad AND 0.1 $<\Omega<$ 2.0

140. If the general practice of radiological protection is satisfactory and the limits of the parameters have been correctly defined, the parameters for most groups of occupational workers should fall within the range 0.1-1.0 rad for $\bar{D}$ and 0.1-2.0 for Ω. In general, the results made available to the Committee suggest that that is the case. Examples of large groups of workers for which it is the case include:

Most workers at most unclear reactors
Fuel manufacture workers in the United Kingdom and the United States
All workers in nuclear power research in Argentina, the United Kingdom and the United States
All industrial workers in the United States
All military workers in the United Kingdom and the United States

All medical, industrial and atomic energy workers in India
All medical and research workers in Thailand
Most medical workers in Switzerland

1. Medical users of diagnostic x rays

141. Bearing in mind the cautions expressed in paragraph 84, it appears that the diagnostic use of x rays in medicine does not lead to high average doses or large proportions of workers receiving annual doses above 1.5 rad. The United Kingdom data for all medical workers, for example, gave values for Ω of 0.90 and for $\bar{D}$ of 0.21 rad. Since the data included radium workers, the average values for radiologists should be even lower. Data supplied for Canada, Denmark, South Africa, Switzerland and the United States would seem to support this conclusion (see paragraphs 84-99).

142. In France, a value for Ω of 0.8 was found together with an annual average dose of 0.13 rad, values close to those found in the United Kingdom. Among medical x-ray workers, only private radiology practitioners show an Ω value appreciably greater than 1.0, namely 1.4, although their annual average dose is 0.22 rad.

143. It has been suggested that, although diagnostic use of x rays does not in general lead to high average occupational doses (with the exception noted above), certain specialized x-ray examinations may well do so. Examples of doses from angiography procedures in Norway have been published (32). Doses were measured during 160 angiography examinations in 10 different hospitals; most doses were low (5 mrad per examination), but in a few cases, particularly of manual procedures, doses of 10-100 mrad were found. The highest doses were due to the use of too large a field and in some cases were associated with manual injection of the contrast medium. The annual number of angiography examinations in Norway were 14 600 in 1970 and 16 580 in 1971, out of a total number of x-ray examinations of about 3 10^6.

144. The dose to the radiologist from cardiac catheterization has been extensively studied by many authors, but the evidence is somewhat conflicting. Some data (70) suggest that the dose to the principal physician may be about 50 mrad to the chest; however, other data (2) suggest that the dose to the trunk area is only 2 mrad. Stacey *et al.* (104) have measured doses to a number of cardiologists. The dose to the chest is low, less than 5 mrad when an undercouch tube is used, but is higher by approximately a factor of three when an overcouch tube is used. Doses of up to 200-300 mrad to the hands were measured. There is, however, a wide variation of dose received by the radiologist, depending on the technique used for each examination.

2. Workers in nuclear medicine

145. There have been some indications that the continual use in diagnosis of short-lived radioisotopes, such as ^{99m}Tc, may contribute considerably to the occupational doses to the staff, although the dose to the patient is less than with longer-lived isotopes. One of the hazards is the irradiation of the fingers from unshielded syringes, and under certain conditions the dose may be as high as 5-10 rad per week (26, 45, 80).

146. The only comprehensive survey known to the Committee is that of the American Association of Physicists in Medicine referred to in paragraph 89 (8). The main objective of this survey was to relate the collective dose to the unit practice, but it was also found that annual average doses were of the order of 0.5 rad (see table 16). On this basis, the occupational doses in nuclear medicine seem to be within the normal range. No value for Ω could be estimated from the survey.

147. The only other sets of data in which nuclear medicine was specifically identified were those from France (table 19) and Australia (table 20). In the French set, if the data for nuclear medicine are compared with those for conventional radiodiagnosis, the Ω value (0.2) is found to be lower, but the annual average dose (0.16 rad) is slightly higher, which shows that annual doses exceeding 1.5 rad are unusual. The Ω value for Australian nuclear medical workers could not be determined, but the average annual dose was very low, only 0.08 rad.

C. GROUPS FOR WHICH $\bar{D} \leqslant 0.1$ rad OR $\Omega \leqslant 0.1$

148. If a given group of workers falls into this category consistently over a number of years, these conclusions can be drawn:

1. Both $\bar{D} \leqslant 0.1$ rad and $\Omega \leqslant 0.1$

149. The workers in the group are most unlikely to receive annual doses exceeding 1.5 rad and the annual average dose is also very low. That implies that these workers may fall into the category defined by the ICRP (51) as not needing individual personal monitoring and health supervision. Examples of workers in this group include:

United Kingdom fuel-enrichment workers
Possibly some Danish medical and industrial workers (although Ω is not known for them)
Workers in chiropractic in Switzerland and possibly also Denmark
Some Canadian industrial workers, e.g. instructors

2. $\bar{D} \leqslant 0.1$ rad but $\Omega > 0.1$

150. The workers in the group may be more likely to receive annual doses exceeding 1.5 rad and therefore there is justification for individual monitoring. The extremely low average dose means, however, that probably more people are included in the monitored group than is justified by the need for protection. Examples of workers in this group include:

Some groups of Canadian medical workers
Dental workers in Canada, Denmark, France and Switzerland

Workers in chiropractic in Canada, Denmark and Switzerland
Veterinarians in Canada and Denmark
Some groups of hospital workers in Denmark
Industrial workers in South Africa
Some medical workers in Switzerland
Some industrial workers in Canada and Denmark
Some groups of workers in Israel

3. $\Omega \leqslant 0.1$ but $\bar{D} > 0.1$

151. The workers in the group would have very nearly the same annual dose. Very few workers would receive doses in excess of 1.5 rad, and the fraction receiving low doses would be less than in the reference distribution. No such distributions have been found in practice.

VIII. OCCUPATIONAL LIFETIME DOSE PREDICTIONS

152. In 1966 the ICRP noted (51) that "any worker who, for prolonged periods, receives doses annually at the maximum permissible levels, might accumulate lifetime doses of the order of hundreds of rems, or, for exposure at the extremities, thousands of rems". The ICRP considered that any limitation of the lifetime accumulated dose in addition to that implied by the maximum permissible dose was not justified, but indicated that the matter was being kept under review.

153. Since to comply with national and international requirements all reporting is of annual doses, data on lifetime cumulative doses have not been readily available. In particular, when high doses are reported for several years, it is not usually clear whether they are high doses to the same or different individuals in successive years. It is the Committee's aim to stimulate publication of figures for cumulative doses to highly exposed individuals from which extrapolations to lifetime doses can be made.

154. Various methods for assessing lifetime doses are available, mainly based on retrospective analysis of individuals or groups who have been employed in the same occupation for a number of years. Although more sophisticated mathematical techniques can be devised, such as that used by Jankowski (55), the Committee felt that the uncertainties introduced by assuming that past doses would be a guide to future doses were sufficiently large that only the simplest mathematical extrapolations were justified. On this basis cumulative lifetime doses have been calculated from the formula

$$D_{40} = (40/n) \sum_{i=1}^{n} \bar{D}_i$$

where $\bar{D}_i$ is the average annual dose for each of the n years over which records are available, and D_{40} is the predicted dose for a 40-year employment. If possible, n should be greater than 5.

155. Where information is available on the numbers of workers with predicted lifetime doses in certain ranges, then the probability of exceeding a given lifetime dose can be calculated for the sample (124) as:

$$P\,[D_{40} > D_j] = 1 - \frac{N_j}{N}$$

where $P[D_{40} > D_j]$ is the probability of receiving a lifetime dose exceeding D_j, N_j is the number of persons in the sample with an estimated lifetime dose less than D_j, and N is the total number of persons in the sample.

A. NUCLEAR POWER INDUSTRY

156. A most useful analysis of lifetime doses along the lines described above has been provided to the Committee (124). The average annual doses for a number of current work groups and for all nuclear station workers at Ontario Hydro in Canada were analyzed as a function of the length of time since the individual was hired as an "Ontario Hydro Radiation Worker". These data are summarized in table 91 (appendix II). Only those groups of workers who had been employed for 5-9 or 10-14 y were used in subsequent analysis. Table 34 shows the results of extrapolating to 40 years, using the average annual doses for these two groups. These are the average lifetime doses for relatively small groups of workers with long service and therefore are reasonably representative; however, it is reasonable to ask what is the probability of a small number of workers reaching higher lifetime doses. Using the method suggested above, the results in table 35 were obtained, showing that the probability of exceeding a lifetime dose of 180 rad is very small (<0.005) for all groups. Even for those in the most exposed group (mechanical maintenance), this probability is less than 0.05 based on the 5-9 y data, but drops to less than 0.01 for the 10-14 y group, as can be seen from figure XXI.

TABLE 34. ESTIMATES OF THE LIFETIME DOSE (D_{40}) FOR WORKERS AT ONTARIO HYDRO IN CANADA

	Lifetime dose estimate (rad)	
Current work group	*A*	*B*
All nuclear station workers	56	39
Operators	78	49
Mechanical maintainers	102	90
Control technicians	51	35

Notes: A—estimates based on workers employed for 5-9 years. B—estimates based on workers employed for 10-14 years.

157. Data have also been provided on termination reports for several categories of United States Nuclear Regulatory Commission licensees (74), two of which are relevant to the nuclear power industry. Termination reports are dose summaries prepared when a monitored individual terminates employment at United States Atomic Energy Commission offices, contractors or covered licensed facilities. These categories are "power reactor and testing facilities" and "fuel processors, fabricators or reprocessors". A summary of the data

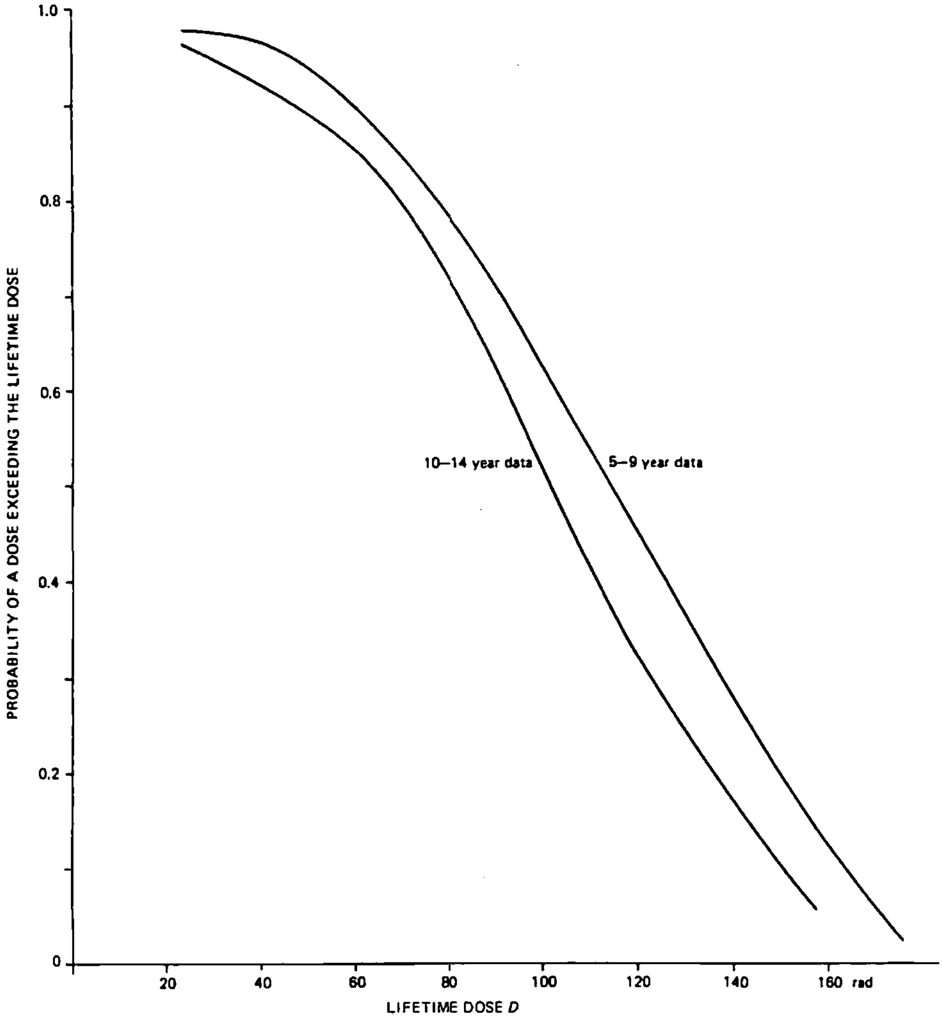

Figure XXI. Probability of exceeding a given lifetime dose for mechanical maintainers at Ontario Hydro, Canada

TABLE 35. ESTIMATES OF THE PROBABILITY OF RECEIVING A LIFETIME DOSE EXCEEDING A SPECIFIED LEVEL FOR WORKERS AT ONTARIO HYDRO, CANADA

Dose level rad	*All nuclear station workers*		*Operators*		*Mechanical maintainers*		*Control technicians*	
	A	*B*	*A*	*B*	*A*	*B*	*A*	*B*
22.5	0.68	0.64	0.89	0.93	0.97	0.95	0.78	0.71
45	0.56	0.44	0.81	0.67	0.95	0.90	0.58	0.47
67.5	0.44	0.21	0.70	0.26	0.85	0.81	0.34	0.12
90	0.31	0.12	0.47	0.09	0.72	0.62	0.24	0
112.5	0.19	0.06	0.32	0.02	0.51	0.38	0.11	0
135	0.11	0.03	0.18	0	0.34	0.24	0.02	0
157.5	0.04	0.01	0.07	0	0.15	0.05	0	0
180	0	0	0	0	0.03	0	0	0
> 200	0	0	0	0	0	0	0	0

Notes: A—estimates based on workers employed for 5-9 years. B—estimates based on workers employed for 10-14 years.

supplied is given in tables 92, 93 and 94 (appendix II). The average annual dose was calculated by dividing the average cumulative dose, excluding those receiving zero or minimal doses, by the mean number of years of employment and is shown in table 36 with the corresponding estimate of the average lifetime dose. The estimated lifetime doses for power reactor workers are similar to the Canadian estimates. The lifetime doses estimated for workers in fuel reprocessing are very much higher, however, owing to the large percentage of terminating workers with high cumulative doses. This is demonstrated in table 37, showing the probability of a lifetime dose exceeding a given level, which indicates that for workers with 5-10 and 10-15 y of employment there is a 50-per-cent probability of a lifetime dose well in excess of 100 rad. Average doses to fuel fabricators and scrap-recovery workers were low and lifetime doses of only 10-15 rad are predicted (see tables 36 and 37).

158. Estimates have also been made of predicted lifetime doses at Windscale (48) to workers who have been employed for 10-15 y. For each individual, the 40-y extrapolated dose was calculated as above if the current cumulative dose divided by the number of years worked was less than 5 rad y^{-1}. Where it exceeded 5 rad y^{-1}, in view of current radiological protection standards at Windscale, which restrict individual doses to less than 5 rad y^{-1}, the lifetime dose was calculated by adding $5(40 - n)$ rad to the worker's current cumulative dose over n years. The results are shown in table 38.

159. Data have been received from the United Kingdom on workers at some Central Electricity Generating Board nuclear power stations whose current cumulative dose exceeded 15 rad (85). These workers had been employed in the nuclear industry for 8-15 y. Their cumulative doses have been extrapolated to 40 y and are shown in table 39. Data have also been received on nine workers at the Central Electricity Generating Board nuclear research laboratories who had cumulative doses exceeding 15 rad up to 1975 (85). The extrapolated lifetime doses are also shown in table 39. These workers had been employed for 10-15 years. The average annual dose to a random sample of 50 workers employed in fuel fabrication, each with over 20 y of occupational exposure, was 0.46 rad (47), leading to an average estimated lifetime dose of 20 rad.

TABLE 36. AVERAGE LIFETIME DOSE FOR WORKERS ASSOCIATED WITH THE NUCLEAR POWER INDUSTRY IN THE UNITED STATES

Based on workers employed for 5-10 or 10-15 years

(rad)

Length of employment (y)	*5-10*	*10-15*
Occupational group		
Power reactor workers	34 (0.85)	19 (0.46)
Fuel reprocessors	145 (3.62)	126 (3.15)
Fuel fabricators and scrap recoverers	15 (0.37)	10 (0.26)

Note: The number in parentheses is the average annual dose (rad) based on the actual doses for each group, omitting workers with zero or minimal doses.

TABLE 37. ESTIMATES OF THE PROBABILITY OF RECEIVING A LIFETIME DOSE EXCEEDING A SPECIFIED VALUE

United States nuclear power industry workers

Dose level (rad)	*Power reactor workers*		*Fuel reprocessors*		*Fuel fabricators and scrap recoverers*	
	A	*B*	*A*	*B*	*A*	*B*
10	0.49	0.39	0.99	1.00	0.28	0.26
20	0.37	0.29	0.93	0.86	0.17	0.15
50	0.22	0.08	0.83	0.71	0.07	0.06
80	0.12	0.05	0.72	0.71	0.05	0.02
100	0.06		0.65		0.03	
130	0.02		0.54		0.02	
> 130						

Notes: A—estimates based on workers employed for 5-10 years. B—estimates based on workers employed for 10-15 years.

TABLE 38. ESTIMATES OF THE LIFETIME DOSE FOR WORKERS AT WINDSCALE, UNITED KINGDOM

Based on workers employed for 10-15 years

Estimated lifetime dose range (rad)	*Number of workers in range*	*Probability of a lifetime dose exceeding the maximum of the range*
0-10	47	0.87
10-20	67	0.70
20-30	41	0.59
30-40	37	0.49
40-50	31	0.41
50-60	35	0.32
60-70	35	0.23
70-80	17	0.18
80-90	13	0.15
90-100	7	0.13
100-110	13	0.09
110-120	7	0.08
120-130	10	0.05
130-140	5	0.04
140-150	9	0.01
150-160	2	0.01
160-170	1	0.01
170-180	0	0.01
180-190	0	0.01
190-200	1	0
200-210	1	

TABLE 39. ESTIMATES OF THE LIFETIME DOSE FOR WORKERS AT UNITED KINGDOM CENTRAL ELECTRICITY GENERATING BOARD SITES

Workers with cumulative doses exceeding 15 rad in 1975

Estimated lifetime dose range (rad)	*Power station*	*Nuclear research laboratory*
	Number of workers	
40-50	11	1
50-60	11	2
60-70	4	3
70-80	2	2
80-90	4	0
90-100	0	1
100-110	1	0
> 110	0	0

B. MEDICAL USES OF RADIATION

160. The average annual doses to medical and allied workers in Australia shown in table 20 have been used to estimate lifetime doses by a rather different procedure, in which the predicted total number of years of occupational exposure is estimated for each category (106) for both male and female workers. The lifetime doses for females are often lower than for males, as their retiring age is generally lower, and in many cases women leave employment for a number of years. The estimate is based on the results of a survey to determine the age and sex distribution in specific occupational categories. The results of this survey are given in table 95 (appendix II). The estimated average lifetime doses for some occupational categories are given in table 40. As might be expected from the low reported dose levels in Australia, the predicted lifetime doses are all low. The highest values are 9-12 rad for clinical and private radiologists.

TABLE 40. ESTIMATES OF THE LIFETIME DOSE TO MEDICAL AND ALLIED WORKERS IN AUSTRALIA

Based on annual average doses[a] and predicted length of exposure

Occupational group[a]	*Predicted length of occupational exposure (y)*		*Estimated average lifetime dose (rad)*	
	Male	*Female*	*Male*	*Female*
Diagnostic radiology				
Hospital radiologists	40	30	7	5
Radiologists, clinics and private	40	30	12	9
Radiographers	40	30	6	4
Assistants	10	10	1	1
Dermatology, gynaecology and radiotherapy				
Dermatologists	40	–	4	–
Assistants	–	30	–	5
Radiographers and gynaecologists	40	30	6	5
Therapy radiographers	35	30	3	3
Assistants	10	10	1	1
Nurses	10	10	4	4
Nuclear medicine				
Radiographers and assistants	40	30	3	2
Dentistry				
Dentists	40	30	< 1	< 1
Nurses and assistants	30	10	< 1	< 1
Chiropractic				
Chiropractors	35	25	1	1
Veterinary				
Veterinary surgeons	35	30	1	1
Assistants	30	5	< 1	< 1

[a] See table 20.

161. Data were received from the United Kingdom on cumulative doses for workers with more than 10 y of employment in South Wales hospitals (27). These results have been extrapolated to give the lifetime doses shown in table 41. Considerably higher than the Australian results, they represent the doses to long-term workers who may have relatively high doses as compared with an overall average such as was used to obtain the Australian figures.

TABLE 41. ESTIMATES OF THE LIFETIME DOSE FOR HOSPITAL WORKERS EMPLOYED FOR MORE THAN 10 YEARS IN SOUTH WALES, UNITED KINGDOM

Estimated lifetime dose range (rad)	*Number of workers in range*	*Probability of a lifetime dose exceeding the maximum of the range*
0-5	32	0.74
5-10	45	0.38
10-15	16	0.25
15-20	6	0.20
20-30	13	0.10
30-40	8	0.03
40-50	1	0.03
50-60	1	0.02
60-70	0	0.02
70-80	1	0.01
> 80[a]	1	

[a] Cumulative dose 154 rad.

162. Estimates of the lifetime dose to broad categories of Japanese workers have been obtained from the average annual doses to personnel with more than 10 y of employment (41). The estimates also take into account the gradual reductions of annual dose during a person's working lifetime. The results are shown in table 42. They are higher than would be obtained by use of only the current average annual dose, as in the Australian study, but lower than extrapolation of the past cumulative dose experience would appear to give. This extrapolation could not be carried out since the average length of employment was not given; but if, for example, all the group B medical workers had been assumed to work for 12 y, the extrapolated 40-y lifetime dose would have been nearly 20 rad rather than 10 rad.

163. It was noted that in New Zealand lifetime doses would be unlikely to exceed a few rads if levels of dose continued as at present (72). Cardiologists and some specialized surgeons carrying out special theatre procedures could receive lifetime surface doses to regions of the head and neck of up to 40 rad assuming a working life of 40 y. It was felt, however, that it would be unusual for a cardiologist to be actively employed in specialized work for so long a period. This observation supports the more widespread use of the Australian technique of taking into account the likely working lifetime in the particular employment causing the dose.

164. In the data from Hungary (15) regarding the most highly exposed workers in a gynaecology department, a number of workers are indicated as having actually been in the institute for 40 y. Their actual estimated lifetime doses are (rad): one physician in gynaecology, 220; two physicians, 40 and 25; two physicians, 80 and 30; one assistant, 140. It is noted, however, that, on the basis of present practice and estimating for the next 40 y, the expected dose to a physician in gynaecology would only

TABLE 42. ESTIMATES OF THE LIFETIME DOSE FOR SOME OCCUPATIONAL CATEGORIES IN JAPAN

Occupational category	*Group*[a]	*Number of workers in group*	*Cumulative dose to 1973 (rad)*	*Annual average dose 1971-1973 (rad)*	*Estimated average lifetime dose (rad)*
Medical	A	32	9	0.28	13
	B	390	6	0.25	10
Atomic energy	A	390	1	0.08	2
	B	421	1	0.07	2
Research and education	A	98	2	0.03	2
	B	196	1	0.05	3
Industrial radiography	B	17	21	0.18	24

[a] A = monitored since 1956; B = monitored since 1961.

be 40 rad. The highest lifetime doses in the department are to a surgeon's assistant (280 rad) and a hospital porter (400 rad).

C. INDUSTRY AND RESEARCH

165. The Australian survey referred to in the previous section also covered industrial and research workers in the same way (106). The results are shown in table 43, and are again very low for the reasons cited above. In the report from New Zealand, it was stated that industrial radiographers would appear to be the group most likely to receive the highest cumulative doses, estimated over a 40-y working life as 20 rad with extreme values perhaps a factor of two greater (72). These estimates are closer to those for Japan shown in table 42, which predict lifetime doses of about 25 rad for industrial radiographers.

166. Analysis of termination reports for industrial radiographer licensees in the United States can be carried out as described in paragraph 157. The data are shown in table 96 (appendix II) (74) and lead to the predicted lifetime doses shown in table 44.

TABLE 43. ESTIMATES OF THE LIFETIME DOSE TO INDUSTRIAL AND RESEARCH WORKERS IN AUSTRALIA

Based on annual average doses[a] and predicted length of exposure

	Predicted length of occupational exposure (y)		*Estimated average lifetime dose (rad)*	
Occupational group[a]	*Male*	*Female*	*Male*	*Female*
Research				
Research workers	25	10	< 1	< 1
Users of enclosed installations	35	30	< 1	< 1
Users of open installations[b]	30	25	7	6
Users of tracers	25	20	2	1
Engineers	35	–	1	–

[a] See table 25.

[b] Including industrial radiographers.

TABLE 44. ANNUAL AND LIFETIME DOSES AND LIFETIME DOSE PROBABILITIES FOR INDUSTRIAL RADIOGRAPHY LICENSEES IN THE UNITED STATES

	Length of employment (y)		
	5-10	*10-15*	*15-20*
Average annual dose[a] (rad)	0.48	0.36	0.34
Estimated lifetime dose (rad)	19	14	14
Probability of a lifetime dose exceeding the rounded dose level (rad)			
10	0.39	0.30	0.39
20	0.27	0.15	0.15
50	0.13	0.08	0.06
80	0.06	0.03	
100	0.02		
130	0.01		

[a] Based on actual doses, omitting workers with zero or minimal doses.

IX. CONCLUSIONS

167. In this report the Committee has tried to identify more clearly the purposes of presenting information on occupational dose statistics other than to demonstrating compliance with regulations. It has also defined those parameters of a dose distribution which are useful for those purposes and for comparison with a reference distribution. The Committee recommends that when data on occupational doses are presented, they should be in such a form that these parameters can be readily extracted. The parameters of interest from a dose distribution are (a) the average dose $\overline{D}$, (b) the fraction of the collective dose received at annual doses above 1.5 rad, (c) the ratio Ω of this collective dose fraction to that of the reference distribution, and (d) the total collective dose or the number of workers. The last two parameters are of more interest if the beneficial results of the practice causing the doses can also be quantified. The Committee also recommends that when workers are classified into particular occupational categories, care

should be taken in defining the categories so that they are clear and mutually exclusive. The definition of the category should be described in detail when doses to workers in a particular category are reported.

168. In the data supplied to the Committee, the benefit derived per unit practice was clearly quantified only in the case of certain sections of the nuclear power industry and one aspect of nuclear medicine. More effort should be expended on this aspect of the justification of radiation exposure.

169. On the basis of a comparison of the parameters describing the occupational dose distribution with those of the reference distribution, a number of specific occupations have been identified which merit continuing surveillance. The group most liable to overexposure are industrial radiographers working with radionuclide sources. Radiological protection for these workers should, if possible, be improved, although it is recognized that it would be extremely difficult to do so in view of their unsupervised working conditions. Medical workers handling radium sources are also liable to receive high doses, but the use of these sources is decreasing. Other medical workers receive very low doses in some countries and comparatively large doses in others. Some groups of workers at nuclear power reactors receive relatively high doses, particularly those engaged in maintenance and health physics work. The highest average doses to groups of workers of moderate numbers were reported for fuel reprocessing workers. Since these were all at one establishment, it is not clear whether doses at these levels are a necessary concomitant to the work. Lung doses to miners are still high but appear to be decreasing. Doses to aircrews form a special case, as they will be uniform and high doses are virtually impossible. These workers constitute a group where individual monitoring is unjustified, but where estimates of doses should continue to be made.

170. A number of groups of workers and occupations have been identified for which $\overline{D} \leqslant 0.1$ rad or $\Omega \leqslant 0.1$. The need for routine individual monitoring of these workers should be kept under review. Examples of these groups are certain categories of medical workers including dentists, chiropractors and veterinarians together with certain industrial workers.

171. A great deal of data has been presented on occupational doses to workers in the nuclear fuel cycle, especially reactor workers. Bearing in mind the uncertainties discussed in paragraph 81, the collective dose per unit electricity generated appears now to be approximately distributed among the activities as shown in table 45.

172. It should be noted that most of the information on which these estimates are based comes from a relatively small number of countries, and the estimates for some parts of the cycle are based only on data from the United Kingdom and the United States. The estimates of collective dose per unit energy generated received in the fuel reprocessing and reactor parts of the cycle are comparable with those made in the 1972 report, 1.6 and 0.7 man rad per MW(e) y, respectively. The increase in collective dose attributable to reactors could be a consequence of the increased maintenance problems with light-water reactors. Associated research and development also makes a large contribution. The dose shown is probably an overestimate, as no deduction was made, in the case of large, diversified organizations, for doses received in work unrelated to the nuclear fuel cycle.

TABLE 45. COLLECTIVE DOSE PER UNIT ENERGY GENERATED RECEIVED IN THE DIFFERENT PARTS OF THE NUCLEAR FUEL CYCLE

Part of cycle	*Occupational collective whole-body dose (man rad per MW(e) y)*
Uranium mining, milling and fuel fabrication	0.2
Reactors	1.0
Fuel reprocessing	1.2[a]
Associated research and development	1.4[b]
Total (rounded)	4

[a] Based only on past experience with the reprocessing of natural uranium, Magnox fuel. Unlikely to be appropriate for the reprocessing of mixed oxide fuel.

[b] Assuming that all the doses incurred are in support of the nuclear fuel cycle.

173. Predictions of expected lifetime doses for workers who spend 40 y at the same job have been made, usually on the basis of linear extrapolation from cumulative doses to workers with 5-15 y of employment. Most of the information from which predictions could be made related to the nuclear power industry, and the situation varied greatly from one country to another. The highest lifetime dose estimates were for fuel reprocessing workers in the United Kingdom and the United States, with a reasonable probability that some workers will receive cumulative lifetime doses exceeding 100 rad, although practically none will be expected to receive more than 200 rad. Workers at power reactors and other jobs associated with the nuclear industry appear more likely to receive maximum lifetime doses of 50-100 rad, but only a few specialized workers will be in this category.

174. On the basis of the data supplied, which is fragmentary and may be biassed towards countries where doses are generally relatively low, lifetime doses to medical workers are unlikely to exceed 50 rad based on current practices. Lifetime doses to workers now reaching the end of their working lives may be considerably greater, but much of the dose will have been received using techniques that are no longer acceptable.

175. Estimates of lifetime doses to industrial workers are also based on scanty data but again appear unlikely to exceed 50 rad. This is the case for industrial radiographers, if the data from termination reports in the United States may be applied elsewhere.

Appendix I

CONSTRUCTION OF THE REFERENCE DISTRIBUTION

1. The distribution of the annual doses x is defined such that:

(a) It is a log-normal distribution as specified in chapter III, paragraph 36;

(b) The average of the annual doses is equal to 0.5 rad;

(c) The probability that an annual dose will lie between 0 and 5 rad is 99.9 per cent.

2. The probability that a value of x will lie between 0 and X is given by

$$P_X = \frac{1}{\sigma\sqrt{2\pi}} \int_0^X \frac{1}{x} e^{-\frac{(\ln x-\mu)^2}{2\sigma^2}} dx$$

Substituting $y = \ln x$ and $Y = \ln X$

$$P_X = \frac{1}{\sigma\sqrt{2\pi}} \int_{-\infty}^{Y} e^{-\frac{(y-\mu)^2}{2\sigma^2}} dy$$

and further substituting $t = \frac{y-\mu}{\sigma}$, the probability becomes

$$P_X = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\frac{Y-\mu}{\sigma}} e^{-\frac{t^2}{2}} dt$$

and can therefore be assessed from tables of the normal distribution. As the reference distribution is defined to have arithmetic mean α = 0.5 rad and $P_{5.0}$ = 0.999, which corresponds to $\frac{Y-\mu}{\sigma}$ = 3.09083, given by the normal distribution tables, it follows that $\frac{\ln 5-\mu}{\sigma}$ = 3.09083. By substitution, $\exp[\ln 5 - 3.090830\sigma + 0.5\sigma^2] = 0.5$, and therefore $\sigma^2 - 6.18166\sigma + 4.60517 = 0$, whence σ = 5.3152 or 0.86641. The second of these values can be shown to be the relevant one by substitution into the formula relating the average dose to the median dose. The desired solution is therefore σ = 0.86641, determining also $\mu = -1.06849$.

3. The following characteristics of the reference distribution may be calculated.

(a) *Probability of the annual dose lying in a certain range*

(i) The probability of an annual dose lying in the range 0-0.5 rad is given by

$$P_{0.5} = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\frac{Y-\mu}{\sigma}} e^{-\frac{t^2}{2}} dt$$

where $\frac{Y-\mu}{\sigma} = (\ln 0.5 + 1.06849)/0.86641 = 0.43322$; therefore

$$P_{0.5} = 0.66756$$

(ii) The probability of an annual dose lying in the range 0-1.5 rad is

$$P_{1.5} = 0.95554$$

(iii) The probability of an annual dose lying in the range 0-5 rad is

$$P_{5.0} = 0.999 \quad \text{(by definition)}$$

(b) *Fraction of the collective dose contributed by a certain dose range*

The mean of all values of the log-normal distribution up to a certain value X is given by

$$\alpha_X = \int_0^X x P(x)\, dx$$

or

$$\alpha_X = \int_0^X \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{(\ln x-\mu)^2}{2\sigma^2}} dx$$

Substituting

$$z = (\ln x - \mu - \sigma^2)/(\sigma\sqrt{2}),\ dz = \frac{1}{\sigma\sqrt{2}} \frac{1}{x} dx$$

$$x = e^{z\sigma\sqrt{2}+\mu+\sigma^2}$$

therefore

$$\alpha_X = \frac{1}{\sqrt{\pi}} e^{\mu+\frac{\sigma^2}{2}} \int_{-\infty}^{(\ln X-\mu-\sigma^2)/(\sigma\sqrt{2})} e^{-z^2} dz$$

Substituting $\frac{t}{\sqrt{2}} = z$

$$\alpha_X = \frac{1}{\sqrt{2\pi}} e^{\mu+\frac{\sigma^2}{2}} \int_{-\infty}^{(\ln X-\mu-\sigma^2)/(\sigma\sqrt{2})} e^{-\frac{t^2}{2}} dt$$

where by definition

$$e^{\mu+\frac{\sigma^2}{2}} = 0.5$$

The fraction of the total collective dose contributed by doses in the range 0 to X is given by

$$S_X = \frac{\alpha_X P_X}{0.5}$$

(i) For annual doses in the range 0-0.5 rad:

$$\frac{\ln X-\mu-\sigma^2}{\sigma\sqrt{2}} = \frac{\ln 0.5+1.06849-0.86641^2}{0.86641\sqrt{2}} = -0.30631$$

$$\alpha_{0.5} = 0.5 \times 0.37969, \text{ and}$$

$$\text{therefore } S_{0.5} = 0.25347$$

(ii) For annual doses in the range 0-1.5 rad:

$$\frac{\ln X-\mu-\sigma^2}{\sigma\sqrt{2}} = \frac{\ln 1.5+1.06849-0.86641^2}{0.86641\sqrt{2}} = 0.59030$$

$$\alpha_{1.5} = 0.5 \times 0.72249, \text{ and}$$

$$\text{therefore } S_{1.5} = 0.69037$$

(iii) For annual doses in the range 0-5 rad:

$$\frac{\ln X-\mu-\sigma^2}{\sigma\sqrt{2}} = \frac{\ln 5.0+1.06849-0.86641^2}{0.86641\sqrt{2}} = 1.57290$$

$$\alpha_{5.0} = 0.5 \times 0.94212, \text{ and}$$

$$\text{therefore } S_{5.0} = 0.94117$$

(c) *Fraction of the collective dose contributed by annual doses within certain dose ranges*

Annual dose range (rad)	*Fraction of workers in dose range*	*Fraction of the collective dose contributed by annual doses in the dose range*
0-0.5	0.668	0.253
0-1.5	0.956	0.690
0-5.0	0.999	0.941

Appendix II

TABLES 46-96

Some of the tables of data supplied to the Committee are collected in this appendix; the table titles are listed below for ease of reference. Except for editing to obtain some uniformity of presentation, the information is reproduced as received.

Table

Table

TABLE 46. FREQUENCY DISTRIBUTION OF RADON EXPOSURE AMONG FRENCH URANIUM MINERS (UNDERGROUND WORKERS), 1971-1975

Year	*Exposure range (fraction of MAC)*[a]									*Mean annual exposure (WL)*
	≤ 0.10	*0.11-0.20*	*0.21-0.30*	*0.31-0.40*	*0.41-0.50*	*0.51-0.60*	*0.61-0.80*	*0.81-1.00*	*> 1.00*	
	Percentage of workers									
1971	36.08	22.39	19.90	13.12	6.22	2.14	0.15			0.18
1972	37.30	22.55	21.13	12.27	4.36	2.24	0.15			0.17
1973	37.70	19.32	19.43	14.40	7.72	1.43				0.18
1974	43.38	26.89	21.46	6.21	1.35	0.71				0.13
1975	53.91	24.71	16.03	4.58	0.66	0.11				0.11

Source: Reference 54.

[a] For each worker the annual exposure is represented by the mean annual air concentration and is expressed as a fraction of the maximum annual concentration (MAC). Given the administrative arrangements and the effective state of equilibrium between radon and its daughters, the MAC is practically equivalent to 1 WL.

TABLE 47. FREQUENCY DISTRIBUTION OF EXTERNAL DOSES TO FRENCH URANIUM MINERS

Year	*Location of work site*	*Annual dose range (rem)*								*Mean annual dose (rem)*
		0-0.5	*0.5-1.0*	*1.0-1.5*	*1.5-2.0*	*2.0-2.5*	*2.5-3.0*	*3.0-4.0*	*4.0-5.0*	
		Percentage of workers								
1971	Underground	35.91	24.71	22.41	11.78	3.01	1.58	0.60		0.88
	Surface	92.19	6.05	0.94	0.67	–	–	0.15		0.25
1972	Underground	34.54	20.91	21.23	12.83	5.86	3.80	0.83		0.97
	Surface	92.57	5.94	0.74	0.37	0.37	–	–		0.21
1973	Underground	42.81	23.43	15.93	11.40	4.84	1.59			0.78
	Surface	92.12	4.87	2.25	0.62	0.14	–			0.18
1974	Underground	48.88	25.55	15.00	7.13	1.78	1.33	0.33		0.67
	Surface	91.91	6.91	0.93	–	0.12	–	0.12		0.18
1975	Underground	63.85	21.04	9.16	3.95	1.35	0.65			0.49
	Surface	94.38	4.81	0.40	0.26	–	0.15			0.13

Source: Reference 54.

TABLE 48. DATA ON NUCLEAR POWER PLANTS IN THE UNITED STATES, 1969-1975

Energy generated, personnel and dose

Plant	*Year*	*Electrical energy generated (MW y)*	*Number of employees*			*Annual collective dose (man rem)*					*Annual average dose (rem)*	*Collective dose per unit energy generated (man rem per MW(e) y)*
			Total	*Contractor*	*Utility*	*Total*	*Operations*	*Maintenance*	*Contractor*	*Utility*		
ARKANSAS 1	75	588.0	147			46					0.31	0.1
Docket 50-313, DPR-51												
First commercial operation-8/74												
Type – PWR												
Capacity – 850 MW												
BIG ROCK POINT	69	43.2	165			136					0.82	3.1
Docket 50-155, DPR-6	70	43.5	290			194					0.67	4.5
First commercial operation-3/63	71	44.4	260			184					0.7	4.1
Type – BWR	72	43.5	195			181					0.92	4.1
Capacity – 72 MW	73	50.9	119			336			140	196	2.8	6.6
	74	40.7	281			276	54	222	42	234	0.98	6.6
	75	35.1	216			180	58	122	20	160	0.83	5.1
BROWN'S FERRY 1	75	328.9	2 380			325					0.14	1.0
Docket 50-259, DPR-33												
First commercial operation-8/74												
Type – BWR												
Capacity – 1 065 MW												
HADDAM NECK	69	397.6	138	75	63	106			27	79	0.77	.5
Docket 50-213, DPR-61	70	424.7	734	657	77	689			463	226	0.94	1.7
First commercial operation-1/68	71	502.2	289	216	73	342			166	176	1.18	.8
Type – PWR	72	515.6	355	285	70	325			181	144	.91	.7
Capacity – 575 MW	73	293.1	841	770	71	673			525	148	0.80	2.1
	74	519.1	550			201					0.37	.4
	75	494.3	795			669	19	650			0.84	1.4
COOPER STATION	75	456.4	175	71	104	96	25	71	16	80	0.55	0.2
Docket 50-298, DPR-46												
First commercial operation-7/74												
Type – BWR												
Capacity – 778 MW												
DRESDEN 1, 2, 3	69	89.4				286						3.2
Docket 50-10, 50-237, 50-249	70	304.0				143						.5
DPR-10, 19, 25	71	394.5				715						1.8
First commercial operation-7/60,	72	1 243.7				728						.6
6/72, 11/71	73	1 112.2	1 341			909	138	771	333	576	0.68	.8
Type – BWR	74	842.5	1 594	318	1 276	1 662			57	1 605	1.04	2.0
Capacity MW 200, 809, 809	75	708.1	3 671	3 076	595	3 209	254	2 955	2 111	1 098	0.87	4.5
FORT CALHOUN	75	252.3	469	369	100	298			93	205	0.63	1.2
Docket 50-285, DPR-40												
First commercial operation-6/74												
Type – PWR												
Capacity – 457 MW												

GINNA	70	268.5	170	56	114	207	94	113	15	192	1.21	.8
Docket 50-244, DPR-18	71	327.8	340	134	206	430	69	361	108	322	1.26	1.3
First commercial operation-3/70	72	295.6	677	266	411	1 032	71	961	278	754	1.52	3.4
Type – PWR	73	409.5	421			244	60	184	91	153	0.58	.6
Capacity – 490 MW	74	253.7	884			1 224					1.38	4.8
	75	365.2	558			496					0.89	1.4
HUMBOLDT BAY	69	40.6	125	41	84	164	69	95	12	152	1.31	4.0
Docket 50-133, DPR-7	70	49.3	115	35	80	209	130	79	37	172	1.81	4.3
First commercial operation-2/63	71	39.6	140	53	87	292	114	178	65	227	2.1	7.7
Type – BWR	72	43.1	127	54	73	253	81	172	57	196	1.99	5.9
Capacity – 65 MW	73	50.1	235			261	59	202			1.11	5.3
	74	43.4	296	221	75	318	103	215			1.07	7.1
	75	45.3	303	230	73	332	128	204	110	222	1.10	7.3
INDIAN POINT 1, 2	69	183.3				298						1.6
Docket 50-3, 50-247, DPR-5, 26	70	43.3				1 639						33.0
First commercial operation-10/62,	71	154.0				768						5.0
8/73	72	142.3				967						6.6
Type – PWR	73	0	2 998			5 134	692	4 442	2 778	2 356	1.71	
Capacity – 265 MW, 873 MW	74	556.1	1 019	114	905	910					0.89	1.6
	75	584.4	480	73	407	626	147	479	42	584	1.3	1.1
KEWAUNEE	75	401.9	54	23	41	25	1	24	11	14	.5	.06
Docket 50-305, DPR-43												
First commercial operation-6/74												
Type – PWR												
Capacity – 560 MW												
LACROSSE	71	33.1	218			158					0.72	5.0
Docket 50-409, DPR-45	72	29.2	151			172					1.13	5.9
First commercial operation-9/69	73	24.4	157			221					1.41	9.1
Type – BWR	74	37.9	115	21	94	139	89	50	6	133	1.21	3.7
Capacity – 50 MW	75	32.0	165			234					1.42	7.3
MAINE YANKEE	73	408.7	422	309	113	121			61	60	0.29	.3
Docket 50-209, DPR-36	74	432.6	620	485	135	420	64	356	188	232	0.68	1.0
First commercial operation-12/72	75	542.9	577	418	159	347	16	331	197	150	0.60	0.6
Type – PWR												
Capacity – 790 MW												
MILLSTONE POINT 1	72	377.6	612	487	125	596	50	546	340	256	0.97	1.6
Docket 50-245, DPR-21	73	225.1	1 152	982	170	620	117	503	395	225	0.54	2.7
First commercial operation-3/71	74	430.3	2 477			1 430					0.58	3.3
Type – BWR	75	465.4	2 587			2 022					0.78	4.3
Capacity – 690 MW												
MONTICELLO	72	424.4	99	9	90	61	40	21	1	60	0.61	.1
Docket 50-363, DPR-22	73	389.5	276	145	131	154	42	112	59	95	0.56	.4
First commercial operation-7/71	74	349.3	842	477	365	349			91	258	0.41	1.0
Type – BWR	75	344.8	1 353			1 353					1.0	3.9
Capacity – 545 MW												
NINE MILE POINT	70	227.0	821	660	161	44	12	32	17	27	0.05	.2
Docket 50-220, DPR-63	71	346.5	1 006	738	268	195	43	152	63	89	0.19	.6
First commercial operation-12/69	72	381.8	735	450	285	285	59	226	28	198	0.38	.8
Type – BWR	73	411.0	550	318	232	517	127	390	108	409	0.94	1.3
Capacity – 610 MW	74	385.9	740	463	277	824	42	782	279	545	1.11	2.1
	75	359.0	649	329	320	681	68	613	203	478	1.04	1.9

TABLE 48 *(continued)*

Plant	*Year*	*Electrical energy generated (MW y)*	*Number of employees*			*Annual collective dose (man rem)*					*Annual average dose (rem)*	*Collective dose per unit energy generated (man rem per MW(e) y)*
			Total	*Contractor*	*Utility*	*Total*	*Operations*	*Maintenance*	*Contractor*	*Utility*		
OCONEE 1, 2, 3	74	724.3	844	253	591	517	18	499	144	373	0.61	.7
Docket 50-269, 270, 287	75	1 838.3	541	112	429	457	66	391	83	374	0.84	.3
DPR-38, 47, 55												
First commercial operation-7/73, 9/74, 12/74												
Type – PWR												
Capacity – 886, 886, 886 MW												
OYSTER CREEK	69	40.1										
Docket 50-219, DPR-16	70	413.6	95	32	63	63	21	42	11	52	0.66	.2
First commercial operation-12/69	71	448.9	249	164	85	240	50	190	92	148	0.96	.5
Type – BWR	72	515.0	339	242	97	582	150	432	167	415	1.71	1.1
Capacity – 650 MW	73	424.6	782	635	147	1 236	195	1 041	683	553	1.58	2.9
	74	434.5	935	346	589	984	166	818	162	822	1.05	2.3
	75	373.6	1 210			1 132	168	964	269	863	0.94	3.0
PALISADES	72	216.8				78						
Docket 50-255, DPR-20	73	286.8	901	608	293	1 109	16	1 093	647	462	1.23	3.8
First commercial operation-12/71	74	10.5	774			627					0.81	60
Type – PWR	75	300.2	474			292					0.62	0.97
Capacity – 821 MW												
PEACH BOTTOM 2, 3	75	1 234.3	971			228					0.84	0.18
Docket 50-277, 278, DPR 44, 56												
First commercial operation-12/74												
Type – BWR												
Capacity – 1 065, 1 065 MW												
PILGRIM	73	484.0	53			74	29	45			1.4	.2
Docket 50-293, DPR-35	74	234.1	454			415					0.91	1.8
First commercial operation-12/72	75	308.1	473			744	132	612	384	360	1.6	2.4
Type – BWR												
Capacity – 655 MW												
SURRY 1 & 2	73	829.4	936			152					0.16	.2
Docket 50-280, 281, DPR-32, 37	74	717.4	1 715			884	72	812			0.52	1.2
First commercial operation-12/72, 5/73	75	1 029.7	808			1 549	25	1 524	1 000	549	1.91	1.5
Type – PWR												
Capacity – 823 MW, 823 MW												
THREE MILE ISLAND 1	75	675.9	168			83			21	62	0.49	0.1
Docket 50-289, DPR-50												
First commercial operation-9/74												
Type – PWR												
Capacity – 819 MW												
TURKEY POINT 3 & 4	73	565.9	444			78					0.18	.1
Docket 50-250, 251, DPR-31, 41	74	966.4	794			454	88	366	202	252	0.57	.5
First commercial operation-12/72, 9/73	75	1 003.7	1 175			875	270	605	558	317	0.74	0.87

Type – PWR												
Capacity – 745 MW												
VERMONT YANKEE	73	222.1	244			85					0.35	.4
Docket 50-271, DPR-28	74	303.5	357			216	24	192	103	113	0.61	.7
First commercial operation-11/72	75	429.0	247	164	83	139	64	75	57	82	0.66	.3
Type – BWR												
Capacity – 514 MW												
YANKEE ROWE	69	123.1	193	117	76	215	46	169	78	91	1.1	1.8
Docket 50-29, DPR-3	70	146.1	355	280	75	255	60	195	98	97	0.71	1.8
First commercial operation-7/61	71	173.5	155	60	95	90	44	46	19	71	0.58	.5
Type – PWR	72	78.7	282	210	72	255	60	195	147	108	0.90	3.2
Capacity – 175 MW	73	127.1	263	158	105	146			70	76	0.56	1.1
	74	111.3	243	149	94	205			99	106	0.84	1.8
	75	145.1	210	134	76	138	62	76	78	60	0.66	1.0
ZION 1, 2	74	425.3	306	87	219	56			13	43	0.18	.2
Docket 50-295, 304, DPR-39, 48	75	1 181.5	1 433	938	495	117	16	101	45	72	.08	0.1
First commercial operation-12/73, 9/74												
Type – PWR												
Capacity – 1 050 MW												
POINT BEACH 1 & 2	72	378.3				580						1.5
Docket 50-266, 301, DPR-24, 27	73	693.7	729			570	70	500			0.78	.8
First commercial operation-12/70,	74	760.2	400			295	70	225	81	214	0.74	.4
4/73	75	801.2	339			456					1.3	0.6
Type – PWR												
Capacity – 497 MW, 497 MW												
PRAIRIE ISLAND 1,2	74	181.9	150	56	94	18			5	13	0.12	.1
Docket 50-282, 306, DPR-42, 60	75	836.0	477			123					0.26	0.15
First commercial operation-12/73, 12/74												
Type – PWR, PWR												
Capacity – 530 MW, 530												
QUAD CITIES 1 & 2	73	1 209.6	533			201	28	173	59	142	0.37	.2
Docket 50-254, 265, DPR-29, 30	74	958.1	678	488	190	482			36	446	0.71	.5
First commercial operation-2/73,	75	833.6	1 972	1 418	554	1 385	98	1 287	592	793	0.70	1.7
3/73												
Type – BWR												
Capacity – 809 MW, 809 MW												
ROBINSON	71	295.3	283	242	41	364	7	357	351	13	1.28	1.2
Docket 50-261, DPR-23	72	580.0	245	147	98	215	42	173	137	78	0.87	.4
First commercial operation-3/71	73	455.1	831			695					0.83	1.5
Type – PWR	74	578.1	853			672	185	487			0.78	1.2
Capacity – 707 MW	75	501.8	849			1 142					1.35	2.3
SAN ONOFRE 1	69	289.8	123	32	91	42	10	32	5	37	0.34	.2
Docket 50-206, DPR-13	70	365.9	251	92	159	155	13	142	59	96	0.61	.4
First commercial operation-1/68	71	362.1	121	12	109	50	12	38	3	47	0.41	.1
Type – PWR	72	372.2	326	141	185	256	29	227	117	139	0.78	.7
Capacity – 450 MW	73	273.7	878	547	331	329	37	292	157	172	0.37	1.2
	74	377.8	219			71					0.32	.2
	75	389.0	424			292					0.75	0.7

Source: Reference 78.

TABLE 49. DISTRIBUTION OF OCCUPATIONAL DOSE TO WORKERS AT FRENCH NUCLEAR POWER PLANTS, 1970, 1971 AND 1974

Dose range (rad)	*1970*	*1971*	*1974*
		Number of workers	
< 0.1	880	970	1 120
0.1-0.2	139	116	
0.2-0.3	83	65	
0.3-0.4	60	44	
0.4-0.5	44	35	
0.5-0.6	38	44	145
0.6-0.7	30	43	
0.7-0.8	21	37	
0.8-0.9	20	28	
0.9-1.0	12	24	
1.0-1.5	57	102	130
1.5-2.0	27	65	105
2.0-2.5	21	35	29
2.5-3.0	26	12	24
3.0-3.5	11	15	11
3.5-4.0	4	5	12
4.0-4.5	1	1	3
4.5-5.0	1	1	2
5.0-6.0	3	2	12
6.0-7.0			2
> 7.0			0
Total	1 478	1 644	1 598
Average annual dose (rad)	0.34	0.39	0.55
Collective dose (man rad)	504	648	879
Ω^a	1.5	1.2	1.7

Sources: References 28, 29, 12 (for 1970, 1971 and 1974, respectively).

[a] Obtained by fitting a log-normal distribution.

TABLE 50. DATA ON NUCLEAR POWER PLANTS IN THE FEDERAL REPUBLIC OF GERMANY, 1973-1975

Energy generated, personnel and dose

					Plant personnel			*External personnel*			*Total personnel*		
Plant		*Year*	*Availability (%)*	*Gross energy (GW(e) h)*	*Number of persons*	*Collective dose (man rem)*	*Average dose (rem)*	*Number of persons*	*Collective dose (man rem)*	*Average dose (rem)*	*Number of persons*	*Collective dose (man rem)*	*Average dose (rem)*
VAK Kahl													
Capacity	16 MW(e)	1973	37.2	50	83	178	2.14	27	10	0.37	110	188	1.77
Type	BWR	1974	67.8	91	87	206	2.37	75	69	0.92	162	275	1.69
First criticality	1961	1975	52.6	76	96	205	2.14	97	69	0.71	193	274	1.42
First commercial operation	11/61												
MZFR Karlsruhe													
Capacity	58 MW(e)	1973	20.2	100	107	83	0.77	87	77	0.88	194	160	0.82
Type	D_2O-PWR	1974	73.1	367	110	66	0.66	70	63	0.90	170	129	0.76
First criticality	5/65	1975	73.6	370	104	58	0.56	75	68	0.91	179	126	0.70
First commercial operation	12/66												
KRB Gundremming													
Capacity	250 MW(e)	1973	79.4	1 727	109	375	3.44	373	286	0.77	482	661	1.37
Type	BWR	1974	88.1	1 920	118	342	2.90	307	323	1.05	425	665	1.56
First criticality	8/66	1975	88.4	1 896	125	304	2.43	324	355	1.10	449	659	1.47
First commercial operation	3/67												
KWL Lingen													
Capacity	252 MW(e)	1973	60.2	1 332	139	158	1.14	141	125	0.88	280	283	1.01
Type	BWR	1974	20.9	481	168	175	1.04	245	253	1.05	413	433	1.05
First criticality	2/68	1975	71.8	1 614	156	228	1.46	577	798	1.38	733	1 026	1.40
First commercial operation	10/68												
AVR Jülich													
Capacity	15 MW(e)	1973	89.8	115	122	45	0.37	4	0	0.1	126	45	0.36
Type	HTR	1974	70.8	91	127	58	0.46	32	2	0.05	159	60	0.37
First commercial operation	1968	1975	37.6	112	128	55	0.43	6	0	0.02	134	55	0.41
KWO Obrigheim													
Capacity	345 MW(e)	1973	89.8	2 629	144	261	1.81	408	415	1.02	552	676	1.22
Type	PWR	1974	92.1	2 570	144	251	1.74	394	335	0.85	538	586	1.09
First commercial operation	4/69	1975	91.5	2 732	146	277	1.90	391	405	1.04	537	682	1.27
KKS Stade													
Capacity	662 MW(e)	1973	73.1	4 131	149	137	0.92	756	266	0.35	905	403	0.44
Type	PWR	1974	92.0	5 328	144	127	0.88	402	172	0.43	546	299	0.55
First criticality	1/72	1975	84.8	4 776	146	162	1.14	473	226	0.48	619	388	0.63
First commercial operation	5/72												

TABLE 50 *(continued)*

Plant		*Year*	*Availability (%)*	*Gross energy (GW(e) h)*	*Plant personnel*			*External personnel*			*Total personnel*		
					Number of persons	*Collective dose (man rem)*	*Average dose (rem)*	*Number of persons*	*Collective dose (man rem)*	*Average dose (rem)*	*Number of persons*	*Collective dose (man rem)*	*Average dose (rem)*
KWW Würgassen													
Capacity	670 MW(e)	1973	49.6	2 065	162	32	0.20	717	63	0.09	879	95	0.11
Type	BWR	1974	11.1	488	173	73	0.42	1 543	425	0.27	1 716	498	0.29
First criticality	10/71	1975	46.3	1 830	178	55	0.31	1 101	166	0.15	1 279	221	0.17
First commercial operation	1972												
KNK Karlsruhe													
Capacity	21 MW(e)	1973	22.2	21	93	5	0.05	73	2	0.02	166	6	0.04
Type	Na-ZrH	1974	34.9	43	97	3	0.03	173	6	0.04	270	10	0.03
First criticality	8/71	1975	0	0	93	15	0.16	136	31	0.23	229	46	0.20
First commercial operation	1973												
Biblis A Biblis													
Capacity	1204 MW(e)	1974	46.7	883	303	1	0.004	10	–	–	313	1	0.004
Type	PWR	1975	82.5	8 419	377	17	0.05	45	2	0.04	422	19	0.05
First criticality	7/74												
First commercial operation	2/75												

Source: Reference 72a.

TABLE 51. DATA RELATING TO OCCUPATIONAL DOSES AT NUCLEAR POWER PLANTS IN SWEDEN, 1971-1975

Plant	*Installed capacity (MW(e))*	*Year*	*Employees (E) or Contractors (C)*	*Collective dose (man rad)*	*Number of persons with registered doses*[a]	*Average annual dose to persons with registered doses (rad)*	*Collective dose per unit energy generated (man rad per MW(e) y)*
Oskarshamm 1 (BWR)	440	1971	E	0	1	0.10	0.38
			C	2	3	0.83	
		1972	E	2	–	–	0.06
			C	8	–	–	
		1973	E	5	–	–	0.09
			C	17	–	–	
Oskarshamm 1 (BWR) Oskarshamm 2 (BWR)	440 580	1974	E	19	91	0.21	0.71
			C	118	578	0.20	
		1975	E	17	81	0.21	0.13
			C	67	448	0.15	
Ringhals 1 (BWR) Ringhals 2 (PWR)	750 820	1974	E	1	1	0.80	0.06
			C	1	5	0.26	
		1975	E	47	277	0.16	0.32
			C	119	723	0.16	
Barsebäcks 1 (BWR)	580	1975	E	5	40	0.13	0.05
			C	5	52	0.09	

Source: Reference 69a.

[a] Persons receiving annual doses in excess of 0.1 rad for 1971-1973 or in excess of 0.03 rad for 1974-1975.

TABLE 52. DISTRIBUTION OF OCCUPATIONAL DOSES TO CONTRACT WORKERS AT TWO SWISS NUCLEAR POWER PLANTS IN 1975

Annual dose range (rad)	*Beznau I and II*	*Mühleberg*
	Number of workers	
< 0.1	64	57
0.1-0.5	63	69
0.5-1.0	28	21
1.0-1.5	18	14
1.5-2.0	6	4
2.0-2.5	11	6
2.5-3.0	4	4
Total	194	175
Collective dose (man rad)	110	82

Source: Reference 61.

TABLE 53. DISTRIBUTION OF OCCUPATIONAL EXTERNAL DOSES AT THE COMISION NACIONAL DE ENERGIA ATOMICA (CNEA) AND ATUCHA NUCLEAR POWER PLANT, ARGENTINA, 1968-1975

	Annual dose range (rad)				
	< 0.1	*0.1-0.5*	*0.5-1.0*	*1.0-5.0*	*> 5.0*
			Number of workers		
CNEA					
1968	584	98	28	14	0
1969	771	96	10	4	0
1970	885	49	7	7	0
1971	842	66	20	13	0
1972	884	44	11	9	0
1973	741	98	18	40	0
1974	713	104	24	15	1
Atucha N.P.P.					
1974	36	201	25	9	0
1975	34	188	71	24	0

Sources: References 21, 25.

TABLE 54. DISTRIBUTION OF OCCUPATIONAL DOSE FROM EXPOSURE TO TRITIUM AT ATUCHA, ARGENTINA, 1974-1975

	Annual dose range (rem)				
Year	*0-0.1*	*0.1-0.5*	*0.5-1.0*	*1.0-5.0*	*> 5.0*
	Number of workers				
1974	242	24	4	1	0
1975	265	43	8	1	0

Note: These values may be overestimated by perhaps a factor of two because of uncertainties in the date of the contamination.

TABLE 55. DATA ON NUCLEAR POWER PLANTS IN THE UNITED KINGDOM

Dose distribution, collective dose and energy

(Number of workers)

	Dose distribution								
	Dose range (rem)								
Plant	*≤ 0.5*	*> 0.5 ≤ 1.5*	*> 1.5 ≤ 4.0*	*> 4.0 ≤ 5.0*	*> 5.0*	*Total*	*Collective dose (man rem)*	*Electricity generated (10^6 MW h)*	*Electricity supplied to grid (10^6 MW h)*
				(a) 1972					
Berkeley	169	198	25	0	0	392	271	2.318	1.954
Bradwell	291	123	1	0	0	415	164	2.123	1.811
Hinkley Point	588	107	22	0	0	717	253	3.530	2.975
Trawsfynydd	242	133	125	12	1	513	575	2.802	2.372
Dungeness	533	11	0	0	0	544	135	3.351	3.230
Sizewell	467	7	0	0	0	474	53	3.236	2.689
Oldbury	425	16	0	0	0	441	75	2.754	2.650
Wylfa	315	0	0	0	0	315	37	2.820	2.418
Hunterston	367	302	4	0	0	673	364	2.576	1.985
				(b) 1973					
Berkeley	202	173	43	0	0	418	302	2.478	2.086
Bradwell	409	98	1	0	0	507	146	1.889	1.606
Hinkley Point	1 083	174	43	1	0	1 301	410	2.796	2.344
Trawsfynydd	357	141	100	0	0	598	430	2.418	2.038
Dungeness	630	3	0	0	0	633	129	3.327	3.207
Sizewell	621	22	3	0	0	646	84	3.469	2.906
Oldbury	399	21	0	0	0	420	73	2.652	2.554
Wylfa	601	0	0	0	0	601	63	3.186	2.604
Hunterston	513	173	4	0	0	690	277	2.293	1.938
				(c) 1974					
Berkeley	182	189	33	0	0	404	284	2.338	1.966
Bradwell	306	92	1	0	0	399	129	2.098	1.787
Hinkley Point	1 331	271	40	0	0	1 642	515	3.657	3.070
Trawsfynydd	466	111	29	0	0	606	260	3.820	3.242
Dungeness	683	3	0	0	0	686	135	3.524	3.401
Sizewell	496	13	5	0	0	514	82	3.762	3.158
Oldbury	404	22	0	0	0	426	71	2.911	2.807
Wylfa	597	0	0	0	0	597	72	4.417	3.723
Hunterston	503	199	16	0	0	718	344	2.467	2.127

Sources: References 39, 85.

TABLE 56. DISTRIBUTION OF EYE DOSE AT FIVE UNITED KINGDOM REACTOR SITES, 1971-1973

(Number of workers)

		Annual dose range (rem)																
Site No.	*Year*	*< 0.99*	*1.00-1.99*	*2.00-2.99*	*3.00-3.99*	*4.00-4.99*	*5.00-5.99*	*6.00-6.99*	*7.00-7.99*	*8.00-8.99*	*9.00-9.99*	*10.00-10.99*	*11.00-11.99*	*12.00-12.99*	*13.00-13.99*	*14.00-14.99*	*> 15*	*Total*
1	1971	440	21	6	4	1	3	1	1									477
	1972	470	21	11	0	2	3	1	0									508
	1973	479	18	3	1	0	0	0	0									501
2	1971	268	79	20	1	0	1	0	1									370
	1972	254	89	12	3	0	0	0	0									358
	1973	234	93	20	5	0	0	0	0									352
3	1971	368	87	55	31	21	7	5	0	2	3	0	0	3	0	0	0	582
	1972	215	83	42	33	24	16	12	13	16	19	15	9	3	8	3	1	512
	1973	295	88	47	34	20	12	5	2	2	2	0	0	0	0	0	0	507
4	1971	480	45	26	17	21	6	5	11	2	2	1	2	2	0	3		623
	1972	532	74	24	21	17	7	6	5	3	3	1	0	0	0	0		693
	1973	618	85	51	33	38	16	11	7	4	2	1	1	0	0	0		867
5	1971	407	0															407
	1972	386	6															392
	1973	361	8															369
	Total	5 807	797	317	183	144	71	46	40	29	31	18	12	8	8	6	1	7 518

Source: Reference 85.

TABLE 57. DISTRIBUTION OF OCCUPATIONAL DOSE TO FUEL-REPROCESSING WORKERS AT WINDSCALE, UNITED KINGDOM, 1971-1975

Dose range (rem)	*1971*	*1972*	*1973*	*1974*	*1975*
	Number of workers				
< 0.5	1 286	1 272	1 195	1 295	1 603
0.5-1.0	377	415	429	459	507
1.0-1.5	193	218	257	313	283
1.5-5.0	583	603	603	649	952
> 5.0	99	144	111	112	36
Total	2 538	2 652	2 595	2 828	3 381
Collective dose (man rem)	3 051	3 379	3 255	3 486	4 028
Average dose (rem)	1.20	1.27	1.25	1.23	1.19

Source: Reference 48.

TABLE 58. DISTRIBUTION OF OCCUPATIONAL DOSE IN BELGIUM, 1973

(Number of workers)

Occupational category	*Annual dose range (rad)*					
	0	*0-0.15*	*0.15-1.5*	*1.5-5.0*	*> 5.0*	*Total*
Medical	856	2 320	1 295	174	2	4 647
All workers	6 547	5 343	3 049	406	16	15 361
Producers (nuclear fuel cycle)[a]	1 055	549	393	127	13	2 137

Source: Reference 73.

[a] Including Mol and Eurochemie.

TABLE 59. DISTRIBUTION OF OCCUPATIONAL DOSE TO UNITED STATES ATOMIC ENERGY COMMISSION (AEC) EMPLOYEES AND CONTRACTORS

(Number of recorded doses)

Year and employee type	*Total number monitored*[a]	*Dose range (rad)*								
		< 1.25	*1.25-2*	*2-3*	*3-4*	*4-5*	*5-6*	*6-7*	*11-12*	*> 12*
1971										
AEC	1 428	1 424	4	–	–	–	–	–	–	–
Contractors	170 259 (75 939)	167 692	1 327	855	262	110	7	3	1	2
1972										
AEC	1 615	1 611	2	1	1	–	–	–	–	–
Contractors	156 905 (69 060)	154 688	1 097	847	185	78	8	2		
		0-1	*1-2*	*2-3*	*3-4*	*4-5*	*5-6*	*6-7*		
1973										
AEC	1 686	1 680	3	3	–	–	–	–		
Contractors	152 431 (62 000)	149 523	1 947	726	172	60	2	1		

Sources: References 111, 112, 113.

[a] The number in parentheses is the number of visitors.

TABLE 60. DISTRIBUTION OF OCCUPATIONAL DOSE RECEIVED BY WORKERS AT UNITED KINGDOM ATOMIC ENERGY AUTHORITY ESTABLISHMENTS, 1971-1974

Dose range (rem)	*1972*	*1973*	*1974*
		Number of workers	
< 1.5	5 949	5 798	6 136
1.5-3	694	648	587
3-4	258	189	142
4-5	152	115	97
5-6	25	4	3
6-7	2	1	1
7-8		1	
8-9	1		
9-10			
> 10		1	2[a]
Total	7 088	6 757	6 968
Collective dose recorded[b] (man rem)	5 021	4 455	3 960
Estimated collective dose for lost films (man rem)	424	437	428
Average dose (rem)	0.71	0.66	0.57

Source: Reference 33.

[a] Unlikely to be doses received by workers.

[b] Including estimated collective dose for lost films.

TABLE 61. DISTRIBUTION OF OCCUPATIONAL DOSE RECEIVED BY WORKERS AT BERKELEY NUCLEAR LABORATORIES, UNITED KINGDOM, 1972-1974

Dose range (rem)	*1972*[a]	*1973*	*1974*
		Number of workers	
≤ 0.5	488	569	630
> 0.5 ≤ 1.5	34	22	18
> 1.5 ≤ 4.0	7	4	1
> 4.0 ≤ 5.0	0	0	0
> 5	0	0	0
Total	529	595	649
Collective dose (man rem)	126	110	98

Source: Reference 85.

[a] Not including contractors.

TABLE 62. OCCUPATIONAL DOSES IN INDIA, 1970-1973

(Number of radiation workers N *and average dose* $\bar{D}$ *(rad))*

	Occupational category							
	Medical		*Industrial*		*Research*		*Atomic energy*[a]	
Year	N[b]	$\bar{D}$[c]	N[b]	$\bar{D}$[c]	N[b]	$\bar{D}$[c]	N[b]	$\bar{D}$[c]
1970	6 059	0.24	1 118	0.40	1 008	0.05	4 094	0.58
1971	6 893	0.25	1 247	0.21	1 294	0.04	4 676	0.38
1972	7 304	0.18	1 538	0.31	1 328	0.03	5 142	0.77
1973	7 739	0.12	1 760	0.32	1 562	0.02	5 578	0.75

Source: Reference 50.

[a] Operations conducted by the Department of Atomic Energy.

[b] Number of radiation workers.

[c] Average dose (rad).

TABLE 63. OCCUPATIONAL DOSES IN THAILAND, 1974

Type of work	*Number of institutions monitored*	*Number of radiation workers*	*Annual average dose (rad)*
Industrial	7	40	0.060
Research	9	53	0.620
Research reactor	1	68	0.547
Medical			
Radium	8	150	0.460
Nuclear medicine	9	303	0.255
X rays	300	1 660	0.120

Source: Reference 94.

TABLE 64. OCCUPATIONAL EXTERNAL DOSES RECORDED BY THE NATIONAL FILM BADGE MONITORING SERVICE IN ISRAEL, 1969-1972

	Annual collective dose (man rad)				*Annual average dose (rad)*			
Type of work	*1969*	*1970*	*1971*	*1972*	*1969*	*1970*	*1971*	*1972*
Medical (diagnostic, therapeutic, dental)	101	89	91	118	0.071	0.063	0.060	0.080
Industrial and agricultural	18	16	12	19	0.076	0.064	0.028	0.046
Research and education	26	16	11	34	0.040	0.023	0.013	0.037
Atomic energy	52	84	79	91	0.057	0.114	0.099	0.114
Overall Ω value[a]	0.9	1.5	2.0	2.1				

Source: Reference 7.

[a] Calculated by fitting a log-normal distribution.

TABLE 65. SUMMARY OF DOSES TO MEDICAL WORKERS IN ILLINOIS, UNITED STATES, 1970

Category	*Number of reports*	*Mean dose (rem per quarter)*	*Collective dose (man rem per quarter)*
Dentists	24	0.024	0.58
Physicians	75	0.043	3.22
Osteopaths	0	0	0
Chiropractors	10	0.003	0.03
Veterinarians	6	0.098	0.59
Podiatrists	0	0	0
Nursing institutions	3	0.023	0.069
Hospitals	1 125	0.085	95.6
Clinics	45	0.080	3.6
Private laboratories	3	0.057	0.17

Source: Reference 64.

TABLE 66. DISTRIBUTION OF OCCUPATIONAL DOSE IN MEDICAL DEPARTMENTS IN DENMARK, 1974

Derived from film badges[a]

	X-ray department (hospitals)	*Lung clinics*	*Surgical department (hospitals)*	*Other departments (hospitals)*	*Dermatologists*	*Hospitals in Greenland*	*Medical practitioners*	*Public dental clinics*	*Chiropractors*	*Veterinary x-ray personnel*	*Isotope laboratories*	*X-ray analysis*	*Industrial x and gamma rays*	*X-ray firms*	*Radium centres*	*Total*
Number of departments	127	40	14	11	30	19	21	10	63	72	122	30	44	15	21	639
	Number of badges															
Dose range (mrem)																
0-10	21 386	2 453	2 126	1 152	985	1 692	1 093	1 028	1 094	1 026	12 588	2 250	2 227	2 068	3 062	56 230
10-50	4 586	286	175	224	177	53	107	33	25	62	454	10	198	128	443	6 961
50-100	430	13	33	28	30	3	8	1	1	11	86	6	100	23	312	1 085
100-400	216	10	8	2	34	1	2	2		2	72	1	90	8	389	837
400-1 000	15		2		5						5		2		21	50
1 000-3 000	3				1									2	3	9
5 000-10 000																
Total	26 641	2 762	2 345	1 407	1 233	1 749	1 210	1 064	1 120	1 101	13 205	2 267	2 618	2 234	4 230	65 186
Number of contaminated films	22										601		2		52	677
Total dose (mrem)	165 154	7 515	8 460	6 575	15 200	1 305	2 820	960	415	2 260	29 940	745	25 850	13 715	114 070	394 984
Mean exposure per film (mrem)	6.2	2.7	3.1	4.5	12.4	0.7	2.3	0.9	0.4	2.0	2.3	0.3	9.8	6.1	26.9	6.1
Number of persons	2 422	251	213	128	112	159	110	97	102	100	1 200	206	238	203	385	5 926
Summary of individual doses	> 5 000 mrem y^{-1}, 0; >500 mrem y^{-1}, 137; > 3 000 mrem in 13 weeks, 0; > 1 500 mrem y^{-1}, 21															

[a] The personal dosimetry service covers about 6000 persons. The films are changed each month, except during June and July, which together make one measuring period.

Source: Reference 118.

TABLE 67. FREQUENCY DISTRIBUTION OF ANNUAL RECORDED OCCUPATIONAL DOSE BY TYPE OF MEDICAL ESTABLISHMENT, FRANCE, 1975

Type of establishment	*Annual dose range (rad)*					*Annual average dose (rad)*	*Number of workers*
	< 0.5	*0.5-1.0*	*1.0-1.5*	*1.5-5.0*	*> 5.0*		
	Percentage of recorded doses						
Radiodiagnostic							
Hospitals	93.0	4.1	1.7	1.0	0.2	0.17	6 787
Private specialized medicine, clinics	88.7	6.1	3.7	1.4	0.1	0.22	1 378
Private radiology	85.0	7.9	4.4	2.5	0.2	0.22	1 101
Private general medicine	92.3	4.2	2.2	1.1	0.2	0.15	625
Industrial medicine, dispensaries	97.7	1.6	0.4	0.3	0.0	0.05	4 194
Dental surgeries, stomatology	99.0	0.7	0.2	0.1	0.0	0.04	2 661
Total	94.3	3.3	1.5	0.8	0.1	0.13	16 746
Radiotherapeutic							
Conventional	87.0	7.8	3.0	2.1	0.1	0.36	713
Curie	87.0	7.7	3.1	2.0	0.2	0.20	484
Cobalt	90.2	5.9	2.1	1.6	0.2	0.17	797
High-energy	88.4	9.2	1.7	0.7	0.0	0.14	456
Nuclear medicine	93.0	5.6	1.1	0.3	0.0	0.16	1 321

Source: Reference 88.

TABLE 68. FREQUENCY DISTRIBUTION OF THE ANNUAL DOSE TO A SAMPLE OF 2579 INDUSTRIAL AND RESEARCH WORKERS IN FRANCE, 1975

Type of work	*Annual dose range (rad)*					*Number of workers*
	< 0.5	*0.5-1.0*	*1.0-1.5*	*1.5-5.0*	*> 5.0*	
	Percentage of workers					
Industrial radiography (x and gamma)	98.6	0.7	0.6	0.1	0.0	839
Research and industrial application of sealed sources	98.2	1.3	0.4	0.1	0.0	752
Other non-medical	91.3	4.1	3.4	1.1	0.1	988

Source: Reference 88.

TABLE 69. FREQUENCY DISTRIBUTION OF DOSES FROM TRITIUM TO FRENCH MEDICAL RESEARCH WORKERS, 1968-1976

Derived from urine monitoring

Year	*Number of workers monitored*	*Dose range (rem)*					*Mean annual dose (rem)*
		< 0.1	*0.1-0.5*	*0.5-1.5*	*1.5-5*	*> 5*	
		Percentage of workers					
1968	37	100	0	0	0	0	< 0.001
1969	112	97.3	1.8	0.9	0	0	< 0.01
1970	124	97.6	2.4	0	0	0	< 0.008
1971	137	99.0	1.0	0	0	0	< 0.003
1972	218	100	0	0	0	0	< 0.002
1973	310	99.7	0.3	0	0	0	< 0.004
1974	379	100	0	0	0	0	< 0.001
1975	465	99.8	0.2	0	0	0	< 0.002
1976	548	98.4	1.1	0.5	0	0	0.012

Source: Reference 88.

TABLE 70. NUMBER AND CATEGORIES OF PERSONS MONITORED FOR EXPOSURE IN NEW ZEALAND, 1975

Category of exposure	*Number of establishments*	*Number of persons*
Medical diagnostic	110	1 200
Medical therapeutic	22	400
Dental	457	1 100
Chiropractic	63	130
Veterinary	72	230
Research and education	19	170
Industrial	36	170
	Total	3 400

Source: Reference 127.

TABLE 71. DISTRIBUTION OF OCCUPATIONAL DOSE BY TYPE OF ESTABLISHMENT, SWITZERLAND, 1974

Annual dose range (rad)	*Industrial*	*Hospital*	*Clinic*	*Medical (private)*	*Dental (private)*	*Chiro-practic*	*Other*
			Number of workers				
< 0.2	240	1 586	715	3 991	3 107	30	946
0.2-0.5	10	140	20	103	61	1	29
0.5-1.5	7	44	5	31	18	0	12
1.5-5.0	1	12	3	11	5	0	1
> 5.0	1	6	1	1	4	0	0
Total	259	1 788	744	4 137	3 195	31	988
Average dose (rad)	0.231	0.139	0.047	0.032	0.089	0.019	0.036
Annual collective dose (man rad)	60	249	35	132	284	1	36

Source: Reference 30.

TABLE 72a. DISTRIBUTION OF OCCUPATIONAL DOSE IN THE GERMAN

(Number and, in parentheses,

Dose range (rad)	*Medicine*						*Universities, schools and nuclear facilities*				
	X	*B*	*R*	*A*	*D*	*T*	*X*	*B*	*R*	*A*	*T*
< 0.49	15 226 (99.2)	530 (78.4)	307 (87.5)	9 (100)	184 (96.4)	16 250 (98.1)	1 627 (99.1)	73 (86.9)	1 574 (85.8)	128 (94.1)	3 402 (92.0)
0.5-1.49	105 (0.7)	95 (14.2)	30 (8.5)		5 (2.6)	235 (1.4)	12 (0.7)	4 (4.8)	155 (8.5)	5 (3.7)	176 (4.8)
1.5-4.99	21 (0.1)	49 (7.2)	11 (3.1)		2 (1.0)	83 (0.5)	4 (0.2)	6 (7.1)	101 (5.5)	3 (2.2)	114 (3.1)
5.0-11.99		1 (0.1)	3 (0.9)			4		1 (1.2)	2 (0.1)		3 (0.1)
12.0-24.99	1					1			1 (0.1)		1
> 25	(0.1)	1				1					
Total	15 357 (92.6)	676 (4.1)	351 (2.0)	9 (0.1)	191 (1.2)	16 580 (100)	1 643 (44.5)	84 (2.3)	1 833 (49.6)	136 (3.7)	3 696 (100)

Source: Reference 65.
Note: X = x rays; B = brachytherapy; R = radionuclide (excluding brachytherapy); A = accelerator; D = deep therapy; T = total.

TABLE 72b. DISTRIBUTION OF OCCUPATIONAL DOSE IN THE GERMAN

(Number and, in parentheses,

Dose range (rad)	*Medicine*						*Universities, schools and nuclear facilities*					
	X	*B*	*R*	*A*	*D*	*T*	*X*	*B*	*R*	*A*	*D*	*T*
< 0.49	17 516 (99.3)	516 (82.0)	398 (93.9)	12 (100)	136 (94.4)	18 578 (98.4)	1 677 (98.7)	136 (90)	1 709 (89.3)	116 (95.9)	36 (92.3)	3 674 (93.6)
0.5-1.49	111 (0.6)	79 (12.6)	22 (5.2)		5 (3.5)	217 (1.3)	20 (1.2)	8 (5.3)	131 (6.8)	5 (4.1)	2 (5.1)	166 (4.2)
1.5-4.99	22 (0.1)	34 (5.4)	4 (0.9)		3 (2.1)	63 (0.3)	2 (0.1)	6 (4.0)	69 (3.6)		1 (2.6)	78 (2.0)
5.0-11.99	3					3		1 (0.7)	6 (0.3)			7 (0.2)
≥ 12.0												
Total	17 652 (93.6)	629 (3.3)	424 (2.2)	12 (0.1)	144 (0.8)	18 861 (100)	1 699 (43.3)	151 (3.8)	1 915 (48.8)	121 (3.1)	39 (1.0)	3 925 (100)

Source: Reference 66.
Note: X = x rays; B = brachytherapy; R = radionuclide (excluding brachytherapy); A = accelerator; D = deep therapy; T = total.

TABLE 72c. DISTRIBUTION OF OCCUPATIONAL DOSE IN THE GERMAN

(Number and, in parentheses,

Dose range (rad)	*Medicine*						*Universities, schools and nuclear facilities*					
	X	*B*	*R*	*A*	*D*	*T*	*X*	*B*	*R*	*A*	*D*	*T*
< 0.49	16 939 (99.5)	395 (71.8)	407 (92.5)	13 (100)	127 (96.1)	17 881 (98.5)	1 323 (99.2)	68 (89.4)	1 810 (86.8)	145 (94.7)	6 (100)	3 352 (91.7)
0.5-1.49	70 (0.4)	105 (19.0)	31 (7.0)		3 (2.3)	209 (1.1)	11 (0.8)	3 (4.0)	188 (9.0)	7 (4.6)		209 (5.7)
1.5-4.99	19 (0.1)	48 (8.7)	2 (0.5)		1 (0.8)	70 (0.4)		3 (4.0)	77 (3.7)	1 (0.7)		81 (2.2)
5.0-11.99		3 (0.5)			1 (0.8)	4 (0.0)		2 (2.6)	7 (0.3)			9 (0.3)
12.0-24.99									1 (0.1)			1 (0.0)
≥ 25.0									2 (0.1)			2 (0.1)
Total	17 028 (93.7)	551 (3.1)	440 (2.4)	13 (0.1)	132 (0.7)	18 164 (100)	1 334 (36.5)	76 (2.1)	2 085 (57.1)	153 (4.2)	6 (0.1)	3 654 (100)

Source: Reference 67.
Note: X = x rays; B = brachytherapy; R = radionuclide (excluding brachytherapy); A = accelerator; D = deep therapy; T = total.

DEMOCRATIC REPUBLIC BY TYPE OF ESTABLISHMENT, 1970
percentage of workers)

Industry				Other					Total						Un-speci-fied
X	R	A	T	X	B	R	A	T	X	B	R	A	D	T	
1 708 (99.0)	1 654 (97.5)	15 (100)	3 377 (98.3)	1 373 (99.5)	3 (100)	784 (96.1)	16 (100)	2 176 (98.2)	19 938 (99.3)	606 (79.6)	4 319 (92.0)	168 (95.5)	184 (96.4)	25 215 (97.3)	4 602 (98.6)
13 (0.8)	33 (1.9)		46 (1.3)	4 (0.3)		26 (3.2)		30 (1.4)	134 (0.6)	99 (13.0)	244 (5.2)	5 (2.8)	5 (2.6)	487 (1.8)	51 (1.2)
4 (0.2)	9 (0.5)		13 (0.4)	2 (0.1)		5 (0.6)		7 (0.3)	31 (0.1)	55 (7.1)	126 (2.7)	3 (1.7)	2 (1.0)	217 (0.8)	11 (0.2)
	1 (0.1)		1	1 (0.1)		1 (0.1)		2 (0.1)	1	2 (0.2)	7 (0.1)			10 (0.1)	2
									1		1			2	
										1 (0.1)				1	1
1 725 (50.2)	1 697 (49.4)	15 (0.4)	3 437 (100)	1 380 (62.3)	3 (0.1)	816 (36.8)	16 (0.7)	2 215 (100)	20 105 (77.6)	763 (2.9)	4 697 (18.2)	176 (0.6)	191 (0.7)	25 932 (100)	4 667

DEMOCRATIC REPUBLIC BY TYPE OF ESTABLISHMENT, 1971
percentage of workers)

Industry				Other					Total						Un-speci-fied
X	R	A	T	X	B	R	A	T	X	B	R	A	D	T	
1 775 (99.2)	1 828 (98.0)	11 (100)	3 614 (98.6)	1 325 (99.6)	1 (100)	885 (95.4)	14 (93.3)	2 225 (97.9)	22 293 (99.2)	653 (83.6)	4 820 (93.9)	153 (96.2)	172 (94.0)	28 091 (97.9)	4 045 (98.2)
15 (0.8)	29 (1.6)		44 (1.2)	2 (0.2)		32 (3.5)	1 (6.7)	35 (1.5)	148 (0.7)	87 (11.2)	214 (4.2)	6 (3.8)	7 (3.8)	462 (1.6)	64 (1.6)
	5 (0.3)		5 (0.1)	3 (0.2)		10 (1.1)		13 (0.6)	27 (0.1)	40 (5.1)	88 (1.7)		4 (2.2)	159 (0.5)	9 (0.2)
	2 (0.1)		2 (0.1)						3	1 (0.1)	8 (0.2)			12	1
1 790 (48.8)	1 864 (50.8)	11 (0.4)	3 665 (100)	1 330 (58.5)	1	927 (40.8)	15 (0.7)	2 273 (100)	22 471 (78.3)	781 (2.7)	5 130 (17.9)	159 (0.5)	183 (0.6)	28 724 (100)	4 119 (100)

DEMOCRATIC REPUBLIC BY TYPE OF ESTABLISHMENT, 1972
percentage of workers)

Industry				Other					Total						Un-speci-fied
X	R	A	T	X	B	R	A	T	X	B	R	A	D	T	
1 607 (99.3)	1 704 (98.0)	11 (100)	3 322 (98.6)	1 180 (100)	5 (100)	326 (93.7)	4 (100)	1 515 (98.5)	21 049 (99.5)	468 (74.0)	4 247 (92.0)	173 (95.5)	133 (96.4)	26 070 (97.5)	7 117 (98.8)
10 (0.6)	32 (1.8)		42 (1.2)			15 (4.3)		15 (1.0)	91 (0.4)	108 (17.1)	266 (5.8)	7 (3.9)	3 (2.2)	475 (1.8)	62 (0.9)
2 (0.1)	4 (0.2)		6 (0.2)			7 (2.0)		7 (0.5)	21 (0.1)	51 (8.1)	90 (2.0)	1 (0.6)	1 (0.7)	164 (0.6)	18 (0.3)
										5 (0.8)	7 (0.2)		1 (0.7)	13 (0.1)	3 (0.0)
											1 (0.0)			1 (0.0)	2 (0.0)
											2 (0.0)			2 (0.0)	1 (0.0)
1 619 (48.2)	1 740 (51.5)	11 (0.3)	3 370 (100)	1 180 (76.8)	5 (0.3)	348 (22.6)	4 (0.3)	1 537 (100)	21 161 (79.2)	632 (2.3)	4 613 (17.3)	181 (0.7)	138 (0.5)	26 725 (100)	7 203 (100)

TABLE 73. DISTRIBUTION OF ANNUAL DOSE RECEIVED BY A SAMPLE OF INDUSTRIAL WORKERS IN THE UNITED KINGDOM, 1974

Dose range (rem)		*Number of workers*
< 0.5		809
0.5-1.0		258
1.0-1.5		38
1.5-5.0		37
> 5.0		3
	Total	1 145

Sources: References 81, 109.

TABLE 74. ANNUAL AVERAGE DOSE IN MEDICINE, RESEARCH AND INDUSTRY IN SEVERAL STATES OF THE FEDERAL REPUBLIC OF GERMANY, AND IN WEST BERLIN, 1969-1974

(rad)

	1969		*1970*		*1971*		*1972*		*1973*		*1974*	
	A	*B*	*A*	*B*	*A*	*B*	*A*	*B*	*A*	*B*	*A*	*B*
Niedersachsen												
Medicine	0.530	0.250	0.460	0.330	0.480	0.320	0.370	0.210	0.320	0.240	0.350	0.120
Research	0.079	1.000	0.120	0.220	0.140	0.089	0.088	0.073	0.094	0.079	0.079	0.130
Industry	1.400	0.245	1.820	0.290	1.230	0.195	0.525	0.110	0.290	0.120	0.170	0.095
Total	0.710	0.210	0.760	0.300	0.560	0.260	0.340	0.170	0.220	0.200	0.190	0.120
Hamburg												
Medicine	0.950	0.260	0.930	0.280	0.970	0.290	0.700	0.220	0.420	0.190	0.310	0.120
Research	0.066	0.160	0.053	0.120	0.070	0.130	0.055	0.200	0.050	0.100	0.031	0.092
Industry	0.290	0.140	0.430	0.100	0.270	0.110	0.260	0.090	0.180	0.080	0.160	0.100
Total	0.330	0.190	0.360	0.180	0.340	0.180	0.270	0.160	0.180	0.130	0.140	0.110
West Berlin												
Medicine	0.190	0.073	0.180	0.092	0.210	0.089	0.200	0.620	0.180	0.062	0.120	0.036
Research	0.075	0.160	0.036	0.160	0.034	0.110	0.017	0.130	0.023	0.120	0.080	0.082
Industry	0.150	0.042	0.320	0.025	0.380	0.040	0.410	0.028	0.350	0.044	0.160	0.020
Total	0.170	0.085	0.160	0.083	0.190	0.083	0.180	0.062	0.160	0.062	0.150	0.035
Schleswig-Holstein												
Medicine	0.800	0.420	1.660	0.610	1.650	0.270	0.048	0.095	0.059	0.170	0.120	0.071
Industry	0	1.640	0	0.160	0	0	0	0	0.100	0.210	0.090	0.021
Total	0.130	0.520	0.650	0.540	0.820	0.230	0.048	0.088	0.029	0.180	0.075	0.072

Source: Reference 10a.
Note: A = radiation sources; B = x rays only.

TABLE 75. DISTRIBUTION OF OCCUPATIONAL DOSE FOR UNITED STATES NUCLEAR REGULATORY COMMISSION LICENSEES NOT CONNECTED WITH THE NUCLEAR POWER INDUSTRY, 1974

Dose range (rad)	*Occupational category* *Industrial radiography*	 *Manufacturing and distribution*
	Number of persons	
Unmeasurable	3 849	1 513
< 0.10	1 740	748
0.10-0.25	939	504
0.25-0.50	635	144
0.50-0.75	424	84
0.75-1.00	323	69
1-2	547	125
2-3	209	59
3-4	74	46
4-5	22	17
5-6	17	21
6-7	5	7
7-8	2	1
8-9	3	2
9-10	0	0
10-11	1	0
11-12	2	0
> 12	0	0
Total	8 792	3 340
Annual collective dose (man rad)	2 938	1 050
Annual average dose (rad), excluding unmeasurable exposures	0.59	0.57
Annual average dose (rad), all exposures	0.33	0.31

Source: Reference 18.

TABLE 76. FREQUENCY DISTRIBUTION OF OCCUPATIONAL DOSE-RATE TO INDUSTRIAL RADIOGRAPHERS IN HUNGARY, 1974

Type of radiography	*Total number of workers*	*Dose-rate range (rad/month)* *< 0.04*	 *0.04-0.4*	 *0.4-1.5*	 *1.5-5.0*
		Percentage of workers			
X-ray	582	97.9	2.0	0.1	
Gamma-ray	1 283	88.6	9.9	1.4	0.1

Source: Reference 15.

TABLE 77. DISTRIBUTION OF ANNUAL DOSE TO INDUSTRIAL WORKERS (OTHER THAN LUMINIZERS AND WORKERS IN THE NUCLEAR INDUSTRY) IN SWITZERLAND, 1969-1975

Dose range (rad)	*1969*	*1970*	*1971*	*1972*	*1973*	*1974*	*1975*
				Number of workers			
< 0.1	580	370	450	560	640	745	1 187
0.1-0.5	90	60	70	80	80	80	158
0.5-1	25	10	15	15	25	40	31
1-1.5	20	2	5	4	5	10	9
1.5-2	8	2	6	1	1	1	5
2-2.5	4	2	0	0	0	1	2
2.5-3	2	2	1	0	0	0	1
3-3.5	5	0	0	0	0	0	0
3.5-5	0	0	0	0	0	0	0
> 5	0	0	0	0	0	1	0
Annual collective dose (man rad)	123	61	66	70	81	114	170

Sources: References 60, 61.

TABLE 78. FREQUENCY DISTRIBUTION OF QUARTERLY DOSES TO SITE RADIOGRAPHERS IN THE UNITED KINGDOM

Firm size (employees)	*Firm No.*	*Dose range (rad)*			
		< 0.375	*0.376-1.25*	*1.26-3.00*	*> 3.00*
		Percentage of doses			
6-10	B 1	25.0	59.1	15.9	0.0
	B 2	26.4	58.5	15.1	0.0
	B 3	60.7	21.4	16.1	1.8
	B 4	28.2	35.6	21.5	14.7
	B 5	76.6	19.4	2.9	1.1
	B 6	71.6	27.8	0.6	0.0
	B 7	43.7	35.7	18.5	2.1
11-20	B 8	56.5	28.0	11.3	4.2
	B 9	41.4	40.4	17.7	0.5
	B 10	43.7	55.0	1.3	0.0
	B 11	23.5	47.3	25.7	3.5
21-50	B 12	48.8	28.2	16.9	6.1
	B 13	65.6	24.0	9.2	1.2
	B 14	45.1	32.6	15.5	6.8
	B 15	43.2	44.2	10.8	1.8
	B 16	51.7	41.0	6.0	1.3
51-200	B 17	48.9	37.0	12.0	2.1
	B 18	62.5	28.6	6.8	2.1
	B 19	53.2	36.0	7.8	3.0
	B 20	59.4	30.9	8.2	1.5
	Overall	52.4	35.2	9.9	2.5

Source: Reference 6.

TABLE 79. FREQUENCY DISTRIBUTION OF QUARTERLY DOSES TO FACTORY RADIOGRAPHERS IN THE UNITED KINGDOM

Firm size (employees)	*Firm No.*	*Dose range (rad)*			
		< 0.375	*0.376-1.26*	*1.26-3.00*	*> 3.00*
		Percentage of doses			
1-5	A 1	100.0	0.0	0.0	0.0
	A 2	60.9	34.8	10.0	4.3
	A 3	62.5	33.3	0.0	4.2
	A 4	67.5	30.0	2.5	0.0
6-10	A 5	92.2	7.8	0.0	0.0
	A 6	100.0	0.0	0.0	0.0
	A 7	98.5	1.5	0.0	0.0
	A 8	41.4	23.0	35.6	0.0
	A 9	86.3	13.7	0.0	0.0
	A 10	92.4	6.3	0.0	1.3
	A 11	100.0	0.0	0.0	0.0
11-12	A 12	39.5	25.3	33.0	2.2
	A 13	96.0	2.0	1.3	0.7
	A 14	64.4	33.1	1.9	0.6
21-50	A 15	62.4	33.1	4.5	0.0
	Overall	72.6	20.0	6.9	0.5

Source: Reference 6.

TABLE 80. DISTRIBUTION OF QUARTERLY WHOLE-BODY DOSES IN EXCESS OF 3 REM RECEIVED BY INDUSTRIAL RADIOGRAPHERS IN THE UNITED KINGDOM, 1969-1974

Quarterly dose range (rem)	*1969*	*1970*	*1971*	*1972*	*1973*	*1974*
			Number of workers			
3.0-3.5	11	8	15	10	5	2
3.5-5.0	26	23	31	13	7	8
5.0-10.0	12	8	11	4	10	6
10.0-25.0	8	9	6	4	7	9
25.0-50.0	1	2	1	2	6	1
50.0-100	4	0	1	0	1	0
> 100	1	0	1	1	1	1
Accurate evaluation not possible	0	1	2	1	1	0

Source: Reference 121.

TABLE 81. ANNUAL DOSE TO LUMINIZERS IN THE UNITED KINGDOM, 1974

Dose range (rem)	*Annual average dose (rem)*	*Number of workers*	*Annual collective dose (man rem)*
< DIL[a]	0.3	89	27
< 1.5[b]	0.5	30	15
1.5-3	2.25	8	18
3-4.5	3.75	6	22
4.5-6	5.25	2	10
6-7.5	6.75	1	7
	Total	136	99

Source: Reference 46.

[a] DIL = derived investigation level (0.05 rad in two weeks). Doses to workers providing samples below the DIL were not recorded. The values in the table are estimates.

[b] Recorded.

TABLE 82. DISTRIBUTION OF DOSES TO TRITIUM LUMINIZERS IN SWITZERLAND, 1969-1975

Dose range (rad)	*1969*	*1970*	*1971*	*1972*	*1973*	*1974*	*1975*
				Number of workers			
< 0.1	3	2	0	0	0	0	3
0.1-0.5	53	43	45	39	58	90	68
0.5-1.0	65	79	67	63	73	78	65
1.0-1.5	68	70	45	57	40	47	52
1.5-2.0	34	41	34	33	28	40	17
2.0-2.5	23	32	16	23	12	15	16
2.5-3.0	27	11	11	7	6	7	7
3.0-3.5	12	11	2	2	2	7	6
3.5-4.0	18	11	4	3	0	4	1
4.0-4.5	9	5	1	1	1	0	
4.5-5.0	4	4	1		0	1	
5.0-5.5	2	2			1	0	
5.5-6.0	5	1				1	
6.0-6.5	0	1					
6.5-7.0	3						
7.0-7.5	3						
7.5-8.0	2						
8.0-8.5	1						
8.5-9.0	0						
9.0-9.5	1						
Annual collective dose (man rad)	618	478	276	268	231	316	239

Sources: References 60, 61.

TABLE 83. DISTRIBUTION OF ANNUAL DOSE TO TRITIUM LUMINIZERS IN FRANCE, 1968-1976

Data derived by urine monitoring

Year	*Dose range (rad)*					*Annual average dose (rad)*
	< 0.1	*0.1-0.5*	*0.5-1.5*	*1.5-5.0*	*> 5.0*	
	Number of workers					
1968	25	–	–	5	–	0.52
1969	17	1	2	4	–	0.47
1970	9	1	1	4	–	0.86
1971	26	5	4	–	–	0.17
1972	25	3	2	3	–	0.29
1973	31	13	15	6	2	0.66
1974	45	11	17	10	1	0.55
1975	49	15	16	10	–	0.49
1976	50	8	15	7	–	0.35

Source: Reference 88.

TABLE 84. DISTRIBUTION OF MEAN ANNUAL DOSE TO WORKERS HANDLING TRITIUM IN THE LUMINOUS PAINT INDUSTRY IN THE FEDERAL REPUBLIC OF GERMANY, 1966-1975

Year	*Number of monitored persons*	*Number of plants*	*Dose range (rad)*				*Annual average dose (rad)*
			< 0.1	*0.1-1.5*	*1.5-5*	*> 5*	
			Percentage of monitored persons				
1966	108	25	34.3	36.1	16.6	13.0	0.87
1967	89	16	33.7	58.4	7.9	0	0.41
1968	108	16	28.7	52.7	16.7	1.9	0.49
1969	99	21	26.3	61.6	11.1	1.0	0.39
1970	124	16	40.0	50.4	8.7	0	0.54
1971	166	22	61.4	28.3	10.2	0	0.78
1972	122	14	58.2	37.7	4.1	0	0.32
1973	78	10	31	40	28	1	1.11
1974	79	12	24	44	31	1	1.08
1975	56	6	39	28	28	5	1.35

Source: Reference 19.

TABLE 85. ANNUAL DOSE TO WORKERS IN THE HUNGARIAN NATIONAL ONCOLOGICAL INSTITUTE, 1936-1975

Period	*Worker category*	*Annual dose (rad)*	*Annual integral dose (g rad)*
1936-1947	Physician	20	860
	Assistant	24	800
	Surgeon's assistant	35	3 700
	Hospital porter	12	200
1947-1957	Physician	1	340
	Assistant	2	640
	Surgeon's assistant	10	2 900
	Hospital porter	12	200
1957-1975	Physician	0.5	170
	Assistant	0.4	270
	Surgeon's assistant	7	2 200
	Hospital porter	10	170

Source: Reference 15.

TABLE 86. ANNUAL AVERAGE DOSE TO GROUPS OF WORKERS AT TRAWSFYNYDD NUCLEAR POWER STATION, UNITED KINGDOM, 1972-1974

Group	*1972*		*1973*		*1974*	
	Number of workers	*Annual average dose (rem)*	*Number of workers*	*Annual average dose (rem)*	*Number of workers*	*Annual average dose (rem)*
Mechanical maintenance	82	0.77	84	1.08	80	0.58
Electrical maintenance	33	0.58	32	0.35	27	0.27
Instrument maintenance	26	0.32	28	0.31	30	0.22
Operations	113	2.23	108	1.38	112	0.80
Health physics	25	3.09	33	1.77	42	1.02
Stores, Station Warden, work study	34	0.19	46	0.20	26	0.17

Source: Reference 85.

TABLE 87. ANNUAL AVERAGE DOSE TO GROUPS OF WORKERS AT HUNTERSTON NUCLEAR POWER STATION "A", UNITED KINGDOM, 1972-1974

Group	*1972*		*1973*		*1974*	
	Average number of workers	*Annual average dose (rem)*	*Average number of workers*	*Annual average dose (rem)*	*Average number of workers*	*Annual average dose (rem)*
Administration	40	0.34	41	0.25	67	0.18
Technical	23	0.33	22	0.20	23	0.16
Health physics						
Monitors	28	0.88	27	0.73	36	0.95
Others	22	0.40	24	0.31	28	0.37
Chemistry	13	0.31	13	0.29	13	0.31
Operations	203	0.52	198	0.47	179	0.51
Maintenance	222	0.56	219	0.42	237	0.55
Fuel handling						
Maintenance	39	0.98	37	0.57	–	–
Others	60	0.62	61	0.42	65	0.44
Contractors	31	1.000	15	0.24	37	0.30
Others	51	0.43	50	0.26	81	0.29

Source: Reference 39.

TABLE 88. AVERAGE ANNUAL DOSE TO GROUPS OF WORKERS AT ONTARIO HYDRO, CANADA

Group	*Length of time employed as an "Atomic Radiation Worker" (y)*	*Average annual dose[a] (rad)*	*Number of workers*
Operators	1-4	1.5	206
	5-9	1.96	188
	10-14	1.23	42
	15-19	0.68	1
	All	1.67	437
Mechanical maintainers	1-4	1.87	182
	5-9	2.55	67
	10-14	2.25	21
	All	2.07	270
Control technicians	1-4	1.00	134
	5-9	1.27	83
	10-14	0.88	17
	All	1.09	234
All nuclear station workers	1-4	0.82	1 355
	5-9	1.39	557
	10-14	0.97	160
	15-19	0.19	5
	20-24	0.73	2
	All	0.98	2 079

Source: Reference 125.

[a] Defined as the total dose received while employed by Ontario Hydro divided by the length of time employed as an Atomic Radiation Worker.

TABLE 89. AVERAGE DOSE RATE TO SOME SELECTED GROUPS OF FUEL REPROCESSING WORKERS AT WINDSCALE, UNITED KINGDOM, 1973-1975

(rem y^{-1})

Group	*1973*	*1974*	*1975*
Operations	3.90 (206)	4.16 (217)	3.15 (293)
Mechanical maintenance	3.30 (131)	2.96 (136)	2.59 (188)
Electrical and instrument maintenance	1.07 (161)	1.03 (169)	1.21 (182)
Health physics	2.02 (85)	1.65 (95)	1.48 (127)
Laboratory services	0.75 (44)	0.48 (50)	0.45 (46)

Source: Reference 48.

Note: The number in parentheses is the number of workers in the group.

TABLE 90. DISTRIBUTION OF DOSES RECEIVED BY WORKERS AT THE RADIOCHEMICAL CENTRE, UNITED KINGDOM, 1972-1974

Dose range (rem)	*1972*	*1973*	*1974*
	Number of workers		
< 1.5	446	527	653
1.5-3	99	87	71
3-4	51	43	49
4-5	18	13	14
> 5	6	1	0
Total	620	671	787
Collective dose (man rem)	690	603	599
Average dose (rem)	1.11	0.90	0.76

Source: Reference 82.

TABLE 91. DISTRIBUTION OF ANNUAL AVERAGE DOSE FOR DIFFERENT GROUPS OF WORKERS AT ONTARIO HYDRO, CANADA

(Number of workers)

Average annual dose (rem)	*Time since hiring as an Ontario Hydro Radiation Worker (y)*				
	1-4	*5-9*	*10-14*	*15-19*	*20-24*
	All nuclear station workers				
≤ 0.49	720	178	58	4	1
0.5-0.99	180	67	32	1	0
1.0-1.49	137	64	37	0	1
1.5-1.99	118	75	13	0	0
2.0-2.49	94	65	10	0	0
2.5-2.99	50	47	5	0	0
3.0-3.49	34	37	4	0	0
3.5-3.99	16	22	1	0	0
4.0-4.49	0	2	0	0	0
4.5-4.99	1	0	0	0	0
≥ 5	5	0	0	0	0
	Reactor operators				
≤ 0.49	51	20	3	0	0
0.5-0.99	20	16	11	1	0
1.0-1.49	29	21	17	0	1
1.5-1.99	33	43	7	0	0
2.0-2.49	40	28	3	0	0
2.5-2.99	18	26	1	0	0
3.0-3.49	9	20	0	0	0
3.5-3.99	4	14	0	0	0
4.0-4.49	0	0	0	0	0
4.5-4.99	0	0	0	0	0
≥ 5	2	0	0	0	0

Average annual dose (rem)	*Time since hiring as an Ontario Hydro Radiation Worker (y)*		
	1-4	*5-9*	*10-14*
		Control technicians	
0.0-0.49	54	18	5
0.5-0.99	23	17	4
1.0-1.49	24	20	6
1.5-1.99	14	8	2
2.0-2.49	6	11	0
2.5-2.99	5	7	0
3.0-3.49	5	2	0
3.5-3.99	2	0	0
4.0-4.49	0	0	0
4.5-4.99	0	0	0
5 or more	1	0	0
		Mechanical maintainers	
0.0-0.49	29	2	1
0.5-0.99	15	1	1
1.0-1.49	17	7	2
1.5-1.99	33	9	4
2.0-2.49	36	14	5
2.5-2.99	21	11	3
3.0-3.49	20	13	4
3.5-3.99	10	8	1
4.0-4.49	0	2	0
4.5-4.99	0	0	0
5 or more	1	0	0

Source: Reference 124.

TABLE 92. DISTRIBUTION OF THE CUMULATIVE DOSE FOR DIFFERENT LENGTHS OF EMPLOYMENT

Derived from termination reports of United States power reactor licensees

Cumulative dose (rad)	*Length of employment (y)*					
	1-5	*5-10*	*10-15*	*15-20*	*20-25*	*> 25*
			Number of workers			
0 or minimal	340	18	10	0	0	4
> 0-0.49	742	39	11	3	0	3
0.5-0.99	163	9	7	1	1	1
1.0-1.9	141	13	5	1	1	1
2.0-2.9	144	14	5	0	0	2
3.0-3.9	81	5	3	1	1	0
4.0-4.9	56	6	3	1	1	0
5.0-9.9	137	17	8	1	0	3
10.0-14.9	25	16	5	1	0	1
15.0-19.9	8	8	1	1	0	0
20.0-25.0	4	7	1	0	0	0
> 25.0	0	3[a]	3[b]	0	1[c]	0

Source: Reference 74.

[a] Average cumulative dose 53 rad.

[b] Average cumulative dose 31 rad.

[c] Cumulative dose 33 rad.

TABLE 93. DISTRIBUTION OF THE CUMULATIVE DOSE FOR DIFFERENT LENGTHS OF EMPLOYMENT

Derived from termination reports of United States fuel reprocessor licensees

Cumulative dose (rad)	*Length of employment (y)* 1-5	5-10	10-15	> 15
	Number of workers			
⩽ 0.99	26	0	0	0
1.0-1.9	23	1	0	0
2.0-2.9	12	2	0	0
3.0-3.9	17	3	1	0
4.0-4.9	17	1	0	0
5.0-9.9	92	7	0	0
10.0-14.9	37	9	1	0
15.0-19.9	15	6	0	0
20.0-25.0	17	9	0	0
> 25.0[a]	12	45	5	0

Source: Reference 74.

[a] The average cumulative doses to the workers in this range are respectively 28, 39, and 52 rad.

TABLE 94. DISTRIBUTION OF THE CUMULATIVE DOSE FOR DIFFERENT LENGTHS OF EMPLOYMENT

Derived from termination reports of United States fuel fabricators and scrap-recovery licensees

Cumulative dose (rad)	*Length of employment (y)* 1-5	5-10	10-15	15-20	20-25	> 25
	Number of workers					
0 or minimal	96	30	16	6	3	0
> 0-0.49	949	196	71	20	12	2
0.50-0.99	222	60	33	14	10	0
1.0-1.9	179	61	55	29	6	1
2.0-2.9	93	33	23	9	4	2
3.0-3.9	41	15	18	5	1	1
4.0-4.9	22	7	8	5	2	1
5.0-9.9	65	34	19	7	6	2
10.0-14.9	17	9	5	5	0	0
15.0-19.9	3	9	8	0	1	0
20.0-25.0	1	6	1	2	0	1
> 25.0[a]	0	8	5	2	0	2

Source: Reference 74.

[a] The average cumulative doses to the workers in this range are respectively, 30, 33, 25 and 51 rad.

TABLE 95. AGE DISTRIBUTION OF PERSONS IN SPECIFIC OCCUPATIONAL GROUPS IN AUSTRALIA

(Percentage)

Occupational group[a]	*Sex*	*Age range (y)* 18-20	21-25	26-30	31-35	36-40	41-45	46-50	51-55	56-60	> 60
Radiologists	M	–	4	26	20	12	13	10	5	5	5
Radiographers	M	17	22	13	12	9	9	6	8	2	2
	F	25	30	12	10	6	6	7	3	1	–
Assistants	F	11	34	19	4	9	10	5	6	1	1
Nurses	F	19	21	18	5	11	8	4	10	3	1
Nuclear medicine	M	4	26	24	22	7	8	6	3	–	–
	F	18	35	21	16	5	2	2	1	–	–
Dentists	M	–	13	19	15	12	11	13	10	4	3
Dental nurses	F	58	31	6	1	2	1	1	–	–	–
X-ray analysts	M	2	16	19	17	16	16	10	4	–	–
Enclosed installations	M	3	5	19	15	20	10	9	13	5	1
Open installations	M	4	16	23	22	11	7	6	10	1	–
Tracers	M	7	24	16	17	11	13	7	3	2	–
Engineers	M	2	14	23	19	8	13	9	5	5	2

Source: Reference 106.

[a] See tables 20 and 25 for fuller description of these occupational groups.

TABLE 96. DISTRIBUTION OF THE CUMULATIVE DOSE FOR DIFFERENT LENGTHS OF EMPLOYMENT

Derived from termination reports of United States industrial radiography licensees

Cumulative dose (rad)	*Length of employment (y)*					
	1-5	*5-10*	*10-15*	*15-20*	*20-25*	*> 25*
	Number of workers					
0 or minimal	1 014	284	153	40	75	386
> 0-0.49	1 758	807	586	161	171	880
0.50-0.99	452	173	159	40	25	100
1.0-1.9	553	231	166	31	24	134
2.0-2.9	370	146	98	18	19	76
3.0-3.9	235	86	64	25	13	65
4.0-4.9	168	79	53	14	13	40
5.0-9.9	284	201	177	42	43	109
10.0-14.9	66	143	94	18	14	37
15.0-19.9	9	65	38	16	11	26
20.0-25.0	2	20	46	6	4	9
> 25.0[a]	8	24	38	18	13	13

Source: Reference 74.

[a] The average cumulative doses to the workers in this range are respectively 60, 34, 36, 63, 51 and 64 rad.

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