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ESTIMATION
DE L'EXPOSITION DE LA POPULATION
AUX RAYONNEMENTS RÉSULTANT DE
LA PRODUCTION D'ÉNERGIE NUCLÉAIRE
ET PROVENANT D'AUTRES SOURCES

INIS

ESTIMATED POPULATION EXPOSURE

FROM NUCLEAR POWER PRODUCTION AND OTHER RADIATION SOURCES

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NUCLEAR ENERGY AGENCY
ORGANISATION FOR ECONOMIC CO-OPERATION AND DEVELOPMENT
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The Organisation for Economic Co-operation and Development (OECD), which was set up under a Convention signed in Paris on 14th December, 1960, provides that the OECD shall promote policies designed:

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The OECD Nuclear Energy Agency (NEA) was established on 20th April 1972, replacing OECD's European Nuclear Energy Agency (ENEA) on the adhesion of Japan as a full Member. NEA now groups all the European Member countries of OECD and Australia, Canada and Japan, with the United States as an Associated country. The Commission of the European Communities takes part in the work of the Agency.

The objectives of NEA remain substantially those of ENEA, namely the orderly development of the uses of nuclear energy for peaceful purposes. This is achieved by:

- *assessing the future role of nuclear energy as a contributor to economic progress, and encouraging co-operation between governments towards its optimum development;*
- *encouraging harmonisation of governments' regulatory policies and practices in the nuclear field, with particular reference to health and safety, radioactive waste management and nuclear third party liability and insurance;*
- *forecasts of uranium resources, production and demand;*
- *operation of common services and encouragement of co-operation in the field of nuclear energy information;*
- *sponsorship of research and development undertakings jointly organised and operated by OECD countries.*

In these tasks NEA works in close collaboration with the International Atomic Energy Agency, with which it has concluded a Co-operation Agreement, as well as with other international organisations in the nuclear field.

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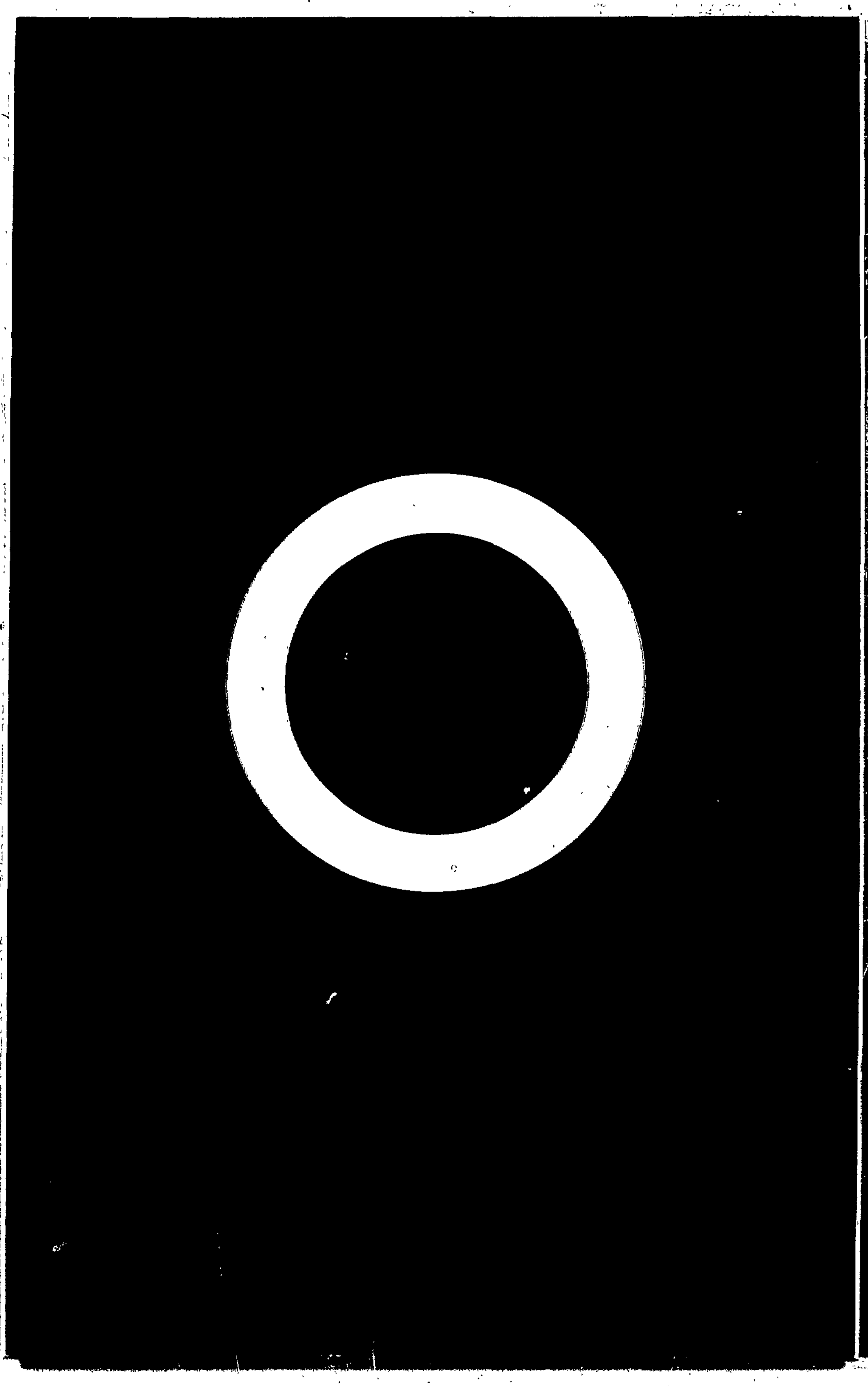
FOREWORD

Radiation protection considerations are an important factor in the development of nuclear energy power. In this respect it is essential to understand the relative significance of all potential sources of radiation exposure of the population.

With this in mind, the Nuclear Energy Agency of the OECD has invited a consultant, Sir Edward Pochin, to prepare a report on this subject.

This report is based on scientific work and is aimed at providing selected background material to be used by representatives of National Authorities having responsibilities in connection with power production and its environmental consequences as well as by other persons interested in this subject.



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SUMMARY

Estimates are given of the total radiation dose from all forms of ionising radiation resulting from nuclear power production. A power consumption of 1 kW per head of population, derived entirely from nuclear energy, would increase the average radiation exposure of the whole population from 100 mrem per year from natural sources (plus about 40 mrem per year from medical procedures and other artificial causes) by about 6 mrem per year. The genetically significant component of this increase would be about 4 mrem per year.

Available estimates of harm from radiation would indicate that this would give a risk per year per million of population of about 1 fatal induced malignancy, about the same number of malignancies fully treatable by operation, and, after many generations, about the same number of inherited defects, of greater or less severity, per year. Accidental injuries, particularly in constructional and mining work, would cause an estimated 1 fatality and 50 other accidents annually.

Indications are given of the number of fatalities and accidents involved in equal power production by alternative methods, and of the value and limitations of such numerical comparisons in reaching decisions on the development of future power programmes.

I. RADIATION EXPOSURE AND ITS EFFECTS

A. INTRODUCTION

1. Throughout the history of the world, mankind has always been exposed to radiation from a variety of natural sources. Within the last thirty years, however, so many additional types of exposure have been developed artificially that it is important to review the amount by which our total exposure has been and will be increased, and the degree of harm which might result.

2. Such a review is greatly simplified by the fact that, for all the different ways in which body tissues are liable to be exposed to radiation, the harmful effects depend essentially upon the amount of energy delivered to the tissues by radiation. Numerous estimates have been made of the amount of energy delivered in this way as a result of exposures of different kinds, both from natural sources and from a variety of artificial ones. These estimates can be used to compare the likely amount, or risk, of harm that may result in an individual exposed to any one of a variety of types or intensities of radiation. Or, when combined with estimates of the numbers of people exposed to a particular source, and the intensity of their exposure, it becomes possible to compare the total harm that may result from different sources of radiation - for example, from a given nuclear power programme, from the present medical use of diagnostic X-rays, from the fall-out from nuclear tests, or from all radiation from natural sources.

3. This simple inter-comparison of the relative importance of different sources of radiation - in terms of the amount of energy delivered to different body tissues and the number of people so exposed - requires qualification in terms of the rate at which the energy is delivered, the "quality" of the radiation (neutrons and alpha radiation being more damaging per unit of energy than X-rays and gamma radiation), and the particular body tissues which are most heavily irradiated. With such qualifications, however, the comparison of expected harm by comparison of energy deposited - the "absorbed dose" of radiation - is broadly valid, and allows the impact of different forms of exposure to be compared with an accuracy sufficient to judge their relative importance biologically.

4. What is at present more difficult, however, is to assess in accurate numerical terms the total amount of harm that may be done by each - the number of cases of leukaemia or fatal cancer induced, the amount of nonfatal illness caused, or the frequency of hereditary disabilities that may result. It is becoming increasingly clear what is the maximum number of such injuries that may be caused by a given radiation exposure. It is increasingly likely that these estimates - based upon the frequency of injuries following large doses - overestimate the frequency that will result from the much smaller doses involved in population exposure. But it cannot yet be said with confidence what amount of harm will actually result from low radiation exposures -- only that the harm would not exceed an amount which is, in fact, likely to be substantially higher than the true amount. The estimates of harm which can be quoted probably, therefore, contain a factor of safety.

The following survey is developed in three stages.

5. Firstly, it is necessary to describe in general terms the way in which radiation damages tissues and may induce disease or genetic abnormalities. It is useful at this stage also to describe the ways in which different activities give rise to irradiation of body tissues, whether by the formation and release of radioactive materials which become incorporated within the body, or by the emission of radiations to which the body is directly exposed.

6. Secondly, it is important then to evaluate the actual size of radiation doses delivered to various tissues, and the number of people so exposed, as a result of different activities and of natural sources. With the qualifications necessary to allow for exposure of different tissues, and for different qualities of radiation, this sets the scene for the inter-comparison of the importance of different activities on the basis of the total energy, or total radiation dose, delivered by each.

7. Thirdly, estimates are reviewed of the types and amounts of harm that may result from these exposures, and so from each of the various sources considered. This is particularly important when comparisons are being made between the harm to be expected, for example from various alternative forms of energy production by nuclear or non-nuclear means. Here, some consideration must be given to the harm to be expected from the alternative methods, and also to the harm that would result from the failure to develop any of the methods. Although the evaluation of harm from other energy sources, or from a deficiency of energy sources, lies outside the scope of the present review, it is important to stress the need for such evaluations and for properly balanced cost-benefit analyses of available alternatives. Some review is therefore given of the type of information needed to make such comparisons of the cost in human harm from non-nuclear energy sources, in parallel to that here attempted for sources involving nuclear processes.

B. HARM CAUSED BY RADIATION

8. The injuries and diseases caused by radiation result, as already mentioned, from the delivery of energy to sensitive body tissues. This holds true for any of the so-called "ionising" forms of radiation. Such radiations give up their energy to any body tissues on which they fall, by causing ionisation of water molecules within these tissues, splitting these molecules into charged ions.* These ions in turn give up their energy to any large molecules on which they become deposited. Delivery of energy in this way to the large desoxyribonucleic acid (DNA) molecules of the cell chromosomes is of particular importance, since the resultant damage to the chemical structure of these DNA chains may alter the genetic information carried by the chromosomes of the cell. Any one of several types of injury may result.

9. Firstly, the cell may die - presumably since the altered sequence of chemical "codons" on the DNA chains no longer constitutes a valid code for the correct continuing formation of protein or other essential substances in the cell. Since the function of most organs can be quite adequately maintained, however, even though two-thirds or more of the organ or tissue is removed, the "cell killing" effects of radiation are only detectable if a large

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*Ultraviolet, visible, infrared and various other forms of radiation are non-ionising, and do not produce the types of tissue damage with which we are here concerned.

proportion of the cells of the organ are killed. Except in the developing embryo, therefore, this effect is only likely to be dominant at very high radiation doses.

10. Similarly, if the damage to a cell prevents the normal division of chromosomes or the transmission of genetic information to daughter cells at the time of cell division, these cells may fail to divide, or daughter cells may fail to develop. In this case the chemical functioning and activity of the original cell may be unimpaired until the time of cell division, and damage may only become manifest at this time. In tissues in which cell division is normally rapid, as for the skin, the bone marrow or the lining of the gut, the normal function of the tissue may be impaired at an early stage if radiation causes the division of cells either to be fatal for the survival of daughter cells, or to be inhibited. Here again, however, effects are only significant if large numbers of cells are affected, following radiation doses much higher than in the forms of population exposure with which this review is concerned, but occurring in types of acute radiation sickness after accidental exposures at high doses approaching those which may prove lethal if the whole of the body is exposed to them.

11. For cells damaged by radiation but surviving the exposure, and capable of producing viable daughter cells when they divide, two possible consequences are important.

12. If the cells concerned are from germinal tissues in the ovary or the testis, and subsequently form fertilised ova or fertilising spermatozoa, then any abnormality in the coding sequence of nucleotides in their DNA may be transmitted to the offspring of the irradiated person. It may be expressed in his children as an illness or abnormality due to an inability to form some protein or enzyme normally, owing to a corresponding defect in the DNA coding sequence for that protein or enzyme. Or it may be expressed as a similar defect, with a resulting clinical abnormality of greater or less severity, in a more remote descendant. Alternatively it may cause failure of the fertilised ovum to develop into a viable foetus, so that no defect is expressed in any liveborn child.

13. If, on the other hand, the damaged cell forms part of any of the other body organs or tissues, damage cannot of course be expressed in the offspring. It does appear likely, however, that "mutations", or abnormalities induced in the DNA sequence of the chromosomes of such body cells by radiation, may sometimes induce changes in the behaviour or properties of the cell so that a cell which normally would only divide rarely, now divides rapidly and a tumour, benign or malignant in character, develops in the irradiated individual, in the organ or tissue of which the cells were irradiated.

14. The mechanism of this cancer inducing, or "carcinogenic", effect of radiation in the exposed tissue is uncertain and may involve changes in the immunological, surface, or other properties of the damaged cell; and these effects may not be due, or due only, to "somatic mutations", or changes in DNA sequence. It is known, however, that ionising radiation can give rise to cancers of most body tissues when these tissues have been very heavily irradiated, for example, in the course of radiotherapy. Moreover, a detectable increase in the occurrence of cancer of several different organs or tissues has been detectable statistically, in epidemiological surveys of people in whom those tissues have been selectively irradiated at much lower doses, as well as in studies on animals. Indeed, for some tissues, and for the body as a whole, it has been possible to estimate the frequency with which malignant tumours (in excess of normal expectation) will develop in man, following known or adequately estimated radiation doses, at these moderate dose levels.

15. One or two instances are known in which a detectable excess of such tumours has followed exposures (of the developing foetus, and of the thyroid gland) at doses which are lower still, and are comparable with those received from natural sources during the course of a lifetime. The unit expressing the absorption of energy from ionising radiation in body tissues is the rad - 1 rad corresponding simply to an "absorbed dose" of 100 ergs of energy per gram of tissue. In radiotherapy, absorbed doses of some thousands of rads are delivered to the tissues treated and at this dose level occasional cancers have been observed in most types of tissue. The epidemiological surveys referred to have detected cancer induction, and in some cases have established its frequency, at doses of a few hundreds of rads, or in the case of the foetus and of the thyroid gland, of only a few rads.

16. The irradiation from natural sources however, typically delivers only about one-tenth of a rad per year to body tissues. Moreover, as will be shown, the average exposure from an extensive world programme of nuclear power production, would add only a few thousandths of a rad (i.e. a few "millirads") per year as the average body exposure throughout the population. While, therefore, the frequency of cancer induction can be estimated for absorbed doses of a few hundred rads, and in certain cases even of a few rads, the frequency and even the occurrence of cancer induction at one thousandth of these dose levels - that is of a few hundred millirads from natural radiation or a few millirads from nuclear power production - is quite uncertain and can only be inferred on a hypothetical basis.

17. The simplest assumption is that the frequency of tumours will be directly proportional to the radiation dose, that is, the number of rads received, regardless of the size of the dose or of the rate at which it is received. Both on experimental grounds, and on the biological evidence for recovery processes that can repair small amounts and low rates of injury, such assumptions are likely to overestimate the frequency with which low doses cause harm, if this frequency is inferred in this way from that observed to follow much higher doses. Such maximum estimates, however, are the only ones which can be asserted with any degree of confidence, until the mechanism of radiation effects and of recovery processes are better understood and it is seen by how much these estimates should be reduced in consequence. Meanwhile they appear to set a limit which the harmful effects of low doses of radiation are unlikely to exceed, and they are used in this way in the following review.

18. We are therefore primarily concerned with so called "somatic" effects, particularly cancer, induced in the irradiated individual, and with "genetic" effects that may be expressed in his descendants. In estimating their frequency, or at least their maximum likely frequency, we need to know the ways in which radiation may reach various body tissues, as well as the doses likely to be delivered to these tissues and the numbers of people who will be exposed to these doses.

C. FORMS OF RADIATION EXPOSURE

19. Ionising radiation may reach the body tissues from sources outside the body by "external radiation", or from radioactive materials within the body or chemically incorporated in the body tissues, as "internal radiation".

20. External radiation may be of many forms - cosmic radiation reaching all mankind from space, X-rays as used in medical diagnosis or in treatment, or gamma radiation, given off during the decay of many radioactive materials.

21. Internal radiation arises from radioactive substances, or "radionuclides", incorporated within the body. Such substances, in the course of their radioactive decay, emit various types of ionising radiation. In many cases this consists both of gamma radiation and of beta radiation which is due to the emission of streams of electrons. A few radioactive materials, and particularly those with the heaviest nuclei, emit alpha radiation which consists in the emission of helium nuclei. Certain radionuclides give off X-rays or positively charged electrons during their decay.

22. These different types of radiation vary very greatly in the maximum depths of tissue through which they penetrate. Gamma radiation and X-rays may pass through many centimetres, before being absorbed. Beta radiation is normally fully absorbed within a few millimetres, and alpha radiation within a few hundredths of a millimetre.

23. Despite this great diversity of types of radiation and of radioactive material, the likelihood of harm resulting in any body tissue can, as already mentioned, be estimated by assessing the dose - the energy delivered by ionising radiation - to that tissue. In many types of exposure from external radiation this is simple, since the whole body and all body organs are about equally exposed, unless the radiation is of very low energy and low penetration through body tissues. For medical exposures to X-rays allowance has to be made for this low penetration, as well as for the part of the body being examined or treated. In most other instances, however, it is adequate to assume that the whole body receives a dose which can be inferred from that measured at any suitable point on the body surface.

24. For internal radiation the problem is quite different, since the radioactive forms of different chemical elements are retained in the particular body organs in which those chemical elements, even in their normal non-radioactive form, become concentrated by the ordinary chemical processes of tissue metabolism. Thus, radioactive forms of iodine become selectively concentrated and retained in the thyroid gland, because they are chemically identical with the normal stable form of iodine, which is taken up by this gland and used for the synthesis of its hormone. Similarly, radioactive caesium is distributed generally throughout the body because caesium, like potassium, is incorporated in all tissue cells, but radio-strontiums become fixed in bone owing to the similarity in metabolism between strontium and calcium. Plutonium, which exists only in radioactive form, is retained predominantly in liver and in bone if inhaled in a soluble form, but very little is absorbed from the gut if it is ingested. If inhaled in the form of insoluble particles, it is largely retained in the lung, however, or in the lymph glands of the lymphatics draining fluid from the lungs.

25. For internal radiation sources, therefore, the estimates of radiation dose to different tissues depend on the chemical properties of the radioactive material concerned and on the solubility of the chemical compound in which it occurs, as well as on the physical properties of its radiations - their type, penetration and persistence, some radionuclides decaying to stable elements very rapidly and other having long half-periods of radioactive decay. Estimates are available, however, for the radiation dose delivered to different tissues by given amounts of the relevant radionuclides, as based on the metabolism of the corresponding elements and upon the routes of intake and the solubilities of the compounds concerned.

26. To an adequate accuracy, therefore, it is possible to specify the total amount of radiation, the "absorbed dose", delivered to the whole body or, in the case of selective internal irradiation, to particular tissues, from the various types of exposure to radiation that may occur. This estimate of the energy delivered by

ionising radiation of all forms from a given source then gives an index of the harm to be expected from that source, provided that allowance is made for any inequality of irradiation of different parts of the body, and, in estimates of subsequent genetic harm, of the age and sex of the subject exposed. However, in the particular case of exposure from alpha radiation or from neutrons and certain other nuclear particles, allowance must also be made for the greater damaging effect - per unit of energy deposited - from these radiations. Indeed, it is convenient, in reviewing the possible harmful effects of exposure to different forms of radiations, to use a measure of tissue dose which incorporates some allowance for this greater effectiveness of certain radiations in causing harm. The "rem" is conventionally used for this purpose, one rem being equivalent to one rad for most forms of radiation. For alpha and neutron radiation, however, one rem corresponds to a lower energy release - typically of about one-tenth or one-twentieth of a rad (5 or 10 ergs per gram) to allow for the higher effectiveness of these radiations.

27. Although for most forms of exposure discussed below, the dosage would be equal whether expressed in rems or rads, it will be less confusing to use one unit throughout. Tissue doses are therefore quoted in rems or in their sub-multiple the millirem (mrem) which is equal to one thousandth of a rem. In the interests of uniformity, this convention is used also in quoting results of published work, i.e. in rems or mrems, even if the original data were quoted in rads or mrads, and even though it is formally incorrect to express in rems, doses higher than those involved in radiation protection.

II. RADIATION FROM NATURAL AND ARTIFICIAL SOURCES

A. RADIATION FROM NATURAL SOURCES

28. Both as an illustration of the estimation of total tissue doses, and in order to give a standard with which other radiation exposures may be compared, it will be useful at this stage to describe the radiation received by the body and by its various tissues from natural sources.

29. This radiation reaches the body in three ways. Firstly, by cosmic radiation originating largely from within our own galaxy, and in part from the sun, particularly during periods of solar activity. Secondly, from certain soils and rocks, producing a radiation field above the surface of the ground. And thirdly, by "internal radiation" from radionuclides incorporated within the body.

30. The intensity of cosmic radiation is greatest at high altitudes since passage through the atmosphere involves the absorbtion of some of the associated energy, as well as changes in the types of particle which constitute the radiation. This variation with altitude is of significance during flight at the altitudes of both subsonic and supersonic aircraft. In assessing the average exposure of most populations however, the variation with altitude is unimportant since the intensity increases by only about 2% per 100 metres and the great majority of populations live within a few hundred metres of sea level.

31. The intensity varies also with latitude, because the earth's magnetic field deflects some of the charged particles of the radiation back into space, and this magnetic field is greater near the equators than near the poles. Although at high altitudes the differences due to latitude are large, at sea level this variation with latitude is not great, differing only by a factor of about 1.5 between latitudes of 30° and 70°. Some variation also occurs during the 11 year solar cycle and during solar flares. Representative average doses can however, be estimated for the great majority of populations.

32. The energy delivered to body tissues by ionisation from all components of cosmic radiation, corresponds to about 33 mrem per year. The absorbtion of this radiation is about equal for all relevant body tissues.

33. A second component is that from soil or from any rock containing appreciable natural radioactivity and lying within a few centimetres of the surface. Such radioactivity is low in most sedimentary rocks but high in rocks such as granites, gneiss and schists which are of igneous origin. Some radiation, constituting about one-third of the total, also arises from a radioactive form of potassium which is constantly present in all biological material and therefore in soils.

34. The radiation received by body tissues from these sources, varies also according to ground cover by moisture in the soil or by snow. It is decreased by shielding due to roads or buildings, and the dose received depends therefore upon the time spent inside or outside buildings. It should be noted however, that building materials themselves may be radioactive, or may release radioactive gases such as radon which may accumulate in the atmosphere within buildings if ventilation is low.

35. For most populations the average exposure from natural terrestrial sources lies between 40 and 50 mrem per year. There are only slight differences in the absorbtion of this radiation by different body tissues, so that the same dose applies to any body organ. Quite large variations, however, occur according to local geological formation. Thus in districts where the underlying rock is of volcanic origin, the average dose rate may be 2 or 3 times the value quoted, as in Colorado and South Dakota [1] and estimated rates of about 100 mrem per year from this source are observed in the French Massif Central, or in the granitic environment of Aberdeen in Scotland.

36. In even more limited areas in South India or in Brazil, the occurrence of a radioactive component in the monazite surface sand involves even higher annual dose rates, reaching levels of up to about 10 times those characteristic for most world populations.

37. For the United States as a whole, the US Environmental Protection Agency [1] estimates an average of 55 mrem per year, and for the United Kingdom, Webb [2] quotes a figure of 38. For world populations the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) [3] have estimated 44 mrem per year, and this value may be taken as typical for populations which are not living in areas of high soil or rock radioactivity.

38. Internal radiation from natural sources is due mainly to the existence of the naturally occurring radioactive component of normal body potassium, the isotope potassium 40*, which, having the normal chemical behaviour of potassium, enters all body cells and tissue fluids and delivers a radiation dose to tissues, varying only according to the cellularity of these tissues. The dose rates from this source have been estimated as about 19 mrem per year to the germinal tissues and 15 mrem to tissues such as the bone marrow and the endosteal cells of bone [3]. Small further doses of about 0.7 mrem per year are due to the radioactive form of carbon of atomic weight 14, this carbon 14 being formed in the atmosphere by the action of cosmic radiation and becoming incorporated in body tissues. Other radioactive materials occurring normally in the biosphere, such as rubidium, polonium, radium, radon and uranium, are responsible for doses of about 8 mrem per year to gonads and bone marrow, and about 35 mrem per year to bone cells. Totals for internal radiation therefore, expressed in mrem per year, are about 28 for germinal tissues, 24 for bone marrow and 51 for the endosteal cells of bone.

39. In sum therefore, taking doses for cosmic radiation and for terrestrial radioactivity as at 33 and 44 mrem per year, natural sources will normally deliver in the region of 100 mrem per year to most body tissues, with somewhat higher values to bone cells owing to the concentration of radioactive substances in bone itself.

40. The exposure attributable to natural sources has been discussed in detail, both to illustrate the ways in which irradiation of body tissues may occur and to demonstrate the manner in which the corresponding total dose is derived.

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*The value 40 refers to the atomic weight of this isotope of potassium.

B. RADIATION FROM ARTIFICIAL SOURCES

41. Similar analyses have been carried out for the exposure of body tissues due to radiological procedures used in medical diagnosis, in radiotherapy and in "nuclear medicine" (which involves the administration of artificial radioactive nuclides for diagnostic and therapeutic purposes).

42. It is unnecessary to describe these derivations in any detail. For normal diagnostic radiology, account is taken of the frequency of different types of examination, and the particular parts of the body exposed directly to the X-ray beam in each case. The dosage to individual tissues of interest, particularly germinal tissue and bone marrow, is estimated from the radiation involved by direct exposure in the beam or by scattered radiation outside the direct beam in each form of examination. With knowledge of the mean dose to the tissue per examination and the frequency of each type of examination in a total population of known size, the mean dose per year can be estimated for selected tissues for the population as a whole. For bone marrow the mean dose, as averaged through the whole population in this way, was found to be 32 mrem per year in a survey made in the UK during 1957/58 [4]. For germinal tissues, a similar dose rate can be derived but, since for these tissues the concern is to estimate the possible induction of genetic defects by radiological procedures, account must be taken of the age and sex of those examined. The "genetically significant dose" to these tissues is therefore derived by combining the estimated radiation exposures of germinal tissues with values for the average numbers of children normally conceived after the ages at which the examinations were performed. The "fertility factor" of probable numbers of live-born children expected at any given age, falls from 2.3 at birth to 0.03 at age 40 to 44 in the female, and from 2.3 to 0.04 at age 45 to 49 in the male in the UK survey [5]. This analysis gave a genetically significant dose from diagnostic X-rays for 1957/58 as equivalent to an average 14 mrem per head of population.

43. Similar estimates for radiotherapy, taking account of the reduction in fertility factor for the majority of patients treated, owing to greater age and diminished survival, added a value of about 5 mrem (for the genetically significant dose, and of 12 mrem for the bone marrow dose). Diagnostic and therapeutic methods in nuclear medicine were responsible for only 0.2 mrem of genetically significant dose (and about 2 mrem per year for bone marrow).

44. Surveys made since this date in a number of different countries have given genetically significant doses ranging mainly from about 10 to 50 mrem per year from diagnostic radiology, and from about 2 to 5 mrem per year from radiotherapy [3]. Those from nuclear medicine have not been found to exceed 1 mrem per year.

45. It is clear therefore, that medical procedures involve an exposure which, when averaged over the whole population, is normally in the region of one-third to one half that from natural causes, in countries with extensive medical facilities. The increasing use of diagnostic X-rays and of nuclear medicine in many countries will tend to raise these contributions to the average radiation of the whole population in the future. This increase is likely however to be at least partly offset by the adoption of techniques involving less radiation exposure per examination - for example, by the use of image intensifiers in diagnostic radiology and of efficient labelling agents such as radioactive technetium and indium in nuclear medicine. Meanwhile medical procedures constitute a major, and as will be seen, the major, present addition to natural radiation in the irradiation of populations.

46. The exposure of world populations from fallout from nuclear tests has been closely examined by UNSCEAR /̄3_7. About a third of the total exposure received, or yet to be received, from tests already conducted, is derived by external radiation from materials which do not enter the body - either from short-lived radionuclides present soon after tests, or from the long-lived caesium 137 which persists for long periods in the environment. A further one-fifth of the total dose commitment is delivered by internal radiation from some of the caesium 137 which enters body tissues and is widely distributed through them, and from strontium 90, which becomes concentrated and retained in bone. The remainder is from carbon 14 formed during the fusion process of the devices tested, most of this exposure being delivered at an extremely low dose rate, but over a long period of time. The estimated average doses take account of those already received and those still to be received from long-lived radionuclides present either in the environment or already in the body. For the world population for all tests prior to 1971, these exposures involve, or will involve, total doses of 120, 180 or 160 mrem to germinal tissues, bone cells or bone marrow respectively. (Tests since 1971 probably add about 10% to these figures). The corresponding values for populations in the Northern Hemisphere, from tests prior to 1971, were estimated as 170, 260 and 220 mrem. The irradiation of tissues at very low dose rates from carbon 14 subsequent to the year 2000, would add about 130, 165 and 130 mrem to these totals for the three tissues respectively. It can thus be stated that all tests up to 1975 have had, or will have had, the effect of adding radiation exposure to populations in the Northern Hemisphere, which is equivalent to about 3 years (2.7, 3.0 and 3.1 years for the three tissues) of natural irradiation.

47. Certain other types of exposure contribute, although to a lesser extent, to the present exposure of populations. Leaving nuclear energy operations for detailed consideration later, we must recognise that various other types of occupational exposure contribute to the total genetically significant dose entering the population as a whole.

48. The annual dose received by any worker who is substantially exposed to radiation during his work needs to be monitored in the course of normal radiation protection measures. This monitoring usually requires only to be approximate, to ensure that permissible levels of exposure are not being approached or exceeded. The external dose is estimated by a radiation sensitive device worn at a position on the body which can sample adequately the exposure received. The internal dose is inferred, as far as possible, by measurements of the body content of the relevant radionuclides or of the rate of their excretion. The accuracy of these estimates is adequate for approximate average doses of workers throughout the occupation to be derived, and these commonly run at about one-tenth of the dose regarded as the maximum permissible dose for any worker in any year. Knowing the total number of workers monitored, an estimate can then be made of the total of all doses received within the occupation, or, taking account of the age and sex distribution of the working population, of the genetically significant dose. This can then be expressed as a genetically significant dose averaged throughout the total population of the country. Various factors decrease the accuracy of these estimates: film badge measurements may not truly sample the dose received by the body as a whole; very low doses may fail to be recorded, or may be recorded for administrative reasons as equal to the lowest detectable by the recording device; and many internal doses are difficult to estimate with any precision. It is clear however, that the contribution to population exposures from these occupational sources, is, in any case, small.

49. UNSCEAR reports details [3] for 12 different countries, of the numbers employed, per thousand of total population, in various occupations involving radiation exposure, and gives the mean external dose received by each. The product of these values then gives total population dose contributions as in Table 1, using average figures for those countries in which records were available. It is unlikely that the mean internal dose would add materially to their values.

Table 1

Occupation	Workers per thousand total population		Mean dose (rem/yr)		Average population dose (mrem/yr)
Medical	0.62	x	0.32	=	0.20
Dental	0.56	x	0.08	=	0.05
Research & Education	0.25	x	0.15	=	0.04
Industrial (non nuclear)	0.11	x	0.31	=	0.03
Total	1.54				0.32

50. Webb [2] has derived average population doses for the UK from occupations involving radiation exposure (namely for medical and dental work, industrial radiography, and for various manufacturing processes) and has estimated genetically significant doses from approximate assumptions of the age distribution of the various working populations. On these assumptions a total population dose of 0.37 mrem per year for non-nuclear occupations corresponded to an estimated genetically significant population dose of 0.28 mrem per year.

51. If this ratio, of genetic to mean occupational dose, is applied to the figures obtained by UNSCEAR, for which genetically significant dose estimations were not obtained, it would suggest that about 0.25 mrem per year of UNSCEAR's estimated average population dose from occupational exposure, was likely to be genetically significant.

52. Certain other activities also make minor contributions to the population exposure [3], probably to a total of about the same magnitude. The average genetically significant dose from radium in luminous watches was estimated to average about 2 mrem per year in 1960, but this figure will have fallen considerably with the increasing use of tritium or promethium as luminising agents. The genetically significant dose from colour television in the United States was estimated as 0.5 mrem per year in 1967, but this figure also will have been considerably reduced by the imposition of performance standards. Other electronic equipment, luminous devices, ceramics containing uranium and other miscellaneous sources contribute small average doses. Nuclear powered cardiac pacemakers are insufficiently widespread in use to contribute significantly to the population total. Passengers and crew in subsonic aircraft are irradiated by cosmic rays at much higher dose rates than prevail at sea level, at about 0.3 mrem per hour, but Webb's estimate for the UK of the contribution to the population genetically significant dose, taking account of man-hours spent in flight and the probable age structure of those flying, is of only 0.08 mrem per year [2].

For supersonic aircraft, the dose rate at likely altitudes of flight is higher by a factor of about 2, but as journey times will be shorter by a corresponding factor, the total dose to passengers will not be substantially different.

53. A total of 0.3 mrem per year was estimated by Webb as the genetically significant whole population dose from all these various minor sources.

54. As a background to our examination of radiation exposure due to a nuclear energy programme, we may therefore summarise the genetically significant population dose from all other recognised sources as in Table 2.

Table 2

All natural sources		100 mrem/yr
From radiological procedures		
Diagnostic	10-50	
Therapeutic	2-5	
Nuclear Medicine	1	
	Total say	35 "
From fallout		
N. Hemisphere, as averaged over the generation most heavily exposed	about	6 "
From occupations, excluding nuclear energy		0.3 "
From other miscellaneous sources		0.3 "
	Total, about	140 mrem/yr

III. EXPOSURES INVOLVED IN NUCLEAR POWER PRODUCTION

A. METHODS OF ESTIMATION AND SUMMATION OF DOSES

55. In reviewing the amounts of radiation exposure due to any programme of nuclear power production, it is necessary:

i) to identify and estimate all radiation doses received by any section of the population from each of the stages involved in the programme - from the first mining of uranium ores to the final disposal of wastes, and

ii) to relate the total exposure from all these contributions, including the total genetically significant dose to the whole population, to the corresponding level of nuclear power production, so that the exposure of the population due to any future level of nuclear power production can be estimated.

56. This integration of all possible contributions to the total exposure cannot be precise. Different types of reactor or reactor fuel involve different forms and levels of exposure. Future developments will entail new techniques, probably with better containment of radioactive material and lower exposures, but also with accumulation or discharge of different forms or proportions of radionuclides. Even the estimation of exposure due to present methods depends upon assumptions of, for example, the exposure of miners as judged from periodic readings of sampling devices in mines, the exposure of local populations near reactors as estimated for assumed population densities, wind directions and weather conditions, or the exposure that might result from liquid waste disposals according to the various possible uses to which "downstream" waters might be put, and which result in human irradiation.

57. Fortunately, however, the adequately accurate estimation of the present exposure of the population is simplified by the fact that the greater part of this total exposure results from components which can be estimated with some confidence and precision. The total exposure of the population is therefore little affected by uncertainty or variations in the exact value of other components. Thus over half of the total genetically significant dose to the population is likely to be contributed by the external exposure of reactor and reprocessing plant workers, and these exposures are controlled and regularly estimated in the individuals concerned.

58. To derive an overall measure of the average exposure of the population, and of its genetic and other significance, adequate accuracy is therefore obtainable by dealing in detail with the main contributions to the total dose and indicating more approximately the size, or the maximum size, of the remaining and smaller components. It will be possible in this way to estimate an average population exposure for a given level of nuclear power production. This exposure can then be compared with the exposure from natural sources and from other artificial sources, to which it would be added. In this

way, for a given power production per head of population, and for a given percentage of this power to be derived from nuclear sources, the percentage increase in the radiation exposure of the population can be derived - the number of millirem per year added to the 140 millirem per year from natural and other artificial sources - for every kilowatt (electrical) per head to be derived from nuclear power. The smaller contributions to harm by localised irradiations of parts of the body must also be reviewed, as must the harm resulting from associated industrial injuries, disease and accidental deaths.

59. It is important that the analysis shall take account of the total dose involved by each year of nuclear power production, including not only the doses received during the year, but also those to which the population is committed by that year of practice and which are received during the future. The estimation of this total "dose commitment" is important, since some radioactive materials persist in the environment or within the body after incorporation, and continue to deliver radiation doses to the population or to the individual after the "year of practice" during which they were formed or released. Estimates of future exposures from current practices are made on the basis of information about the persistence and circulation of such longlived materials in the environment. In some instances, present levels of environmental radioactivity reflect past as well as current releases of activity, and correction is then made to infer the levels that would correspond to prolonged releases at a given level, and so the total dose commitments that would result from continuing work at that level.

60. It will be convenient to express the total exposure of populations from particular sources as the "collective doses" due to these sources. These collective doses are expressed in man.rems, and represent the average dose (or, where longlived materials are involved, the average dose commitment) in rems, throughout the population, multiplied by the number of persons in the population over which the average is made. The total exposure from a given level of power production can then be readily estimated if the exposure at each stage and for every population group exposed, is expressed as the total collective dose per unit of corresponding electrical power production by nuclear energy - i.e. as man.rems per megawatt of electricity so generated during one year - "man.rem/MW(e)y". This collective dose (strictly the collective dose commitment) will ordinarily refer to the dose to the body as a whole; when that to a particular organ only is intended, this will be specified - e.g. as man.rem to thyroid glands.

61. A population of a million people, each consuming one kilowatt of electrical energy derived from nuclear power, would require an output of 1000 MW(e), or about the rated capacity of one large reactor. When the frequency of accidental deaths is estimated, these are given as an annual rate per 1000 MW(e)y.

B. STEPS INVOLVED IN NUCLEAR POWER PRODUCTION

62. The normal process of nuclear power generation involves a series of steps, for each of which the exposures to radiation and other hazards need to be reviewed. (Table 3).

The following steps are involved:

i) Construction of installations.

ii) Mining of uranium ore.

iii) Milling of ores.

Table 3

Collective whole body doses, partial body exposures and occupational fatality rates occurring at different stages of nuclear power production process

Stage	Whole body exposures (man.rem/MW(e)y)		Partial body exposures	Fatal occupational accidents and diseases per 1000 MW(e)y
	Population	Occupational		
Construction of installations	-	-	-	0.25
Uranium Mining	-	External, to miners 0.1	Lung, miners	0.4
Milling and processing	-	(Probably less than 0.1)	Lung and hands slight	say 0.1
Fabrication and enrichment	-	-	Probably slight	-
Reactor operation	Liquid wastes 0.002 Gaseous wastes 0.1	From activation and fission products (external and tritium) 2.0	-	0.02
Reprocessing plants	Liquid wastes 0.1 Gaseous wastes 0.25 C14 1.0*	From activation and fission products (mainly external) 2.0	Occupational, to lung and other tissues occasionally Public, to skin, intestine, thyroid and bone for small groups	0.02
Other fuel steps	-	0.03	-	-
Transport	0.004	0.005	-	0.003
Accidents	0.05	-	-	
Total	1.5	+ 4.2	See text	0.8
Total (genetically significant)	1.5	+ 2.7	-	

*From reactors; discharges from reprocessing plants at present uncertain. Total dose commitment to future: 0.05 in first 30 years.

iv) Fabrication of fuel elements, either from uranium with or without "enrichment" or, for fast reactors, from plutonium derived from reprocessing plants.

v) Reactor operation.

vi) Reprocessing of irradiated fuel.

vii) Transport of fuel or waste material.

viii) Waste disposal from reactors.

ix) Waste disposal from reprocessing plants.

In addition, consideration needs to be given to:

x) Possible accidental discharges.

xi) Decommissioning of installations.

1. Construction of installations

63. No appreciable exposure to any form of radioactive material is involved at this stage except during the assembly of reactor cores. Here the sealing of fuel elements and the methods used for their manipulation should effectively eliminate any possibilities of significant radiation exposure, or of harm from the chemical toxicity of uranium.

64. Construction work however does involve a substantial hazard of accidental injuries and deaths, typically with 2 to 8 deaths per 10,000 man-years of work [6, 7], the higher of these levels applying to the type of heavy operations involved in reactor construction.

2. Mining of uranium ores

65. The chief radiation hazard of uranium mining is due to the release of the radioactive gas radon (Rn-222), which is formed during the decay of radium, and the inhalation of biologically significant amounts of this gas if ventilation of the mine is inadequate. Decay products of the gas become deposited on the walls of the respiratory passages, and deliver a radiation dose to the cells of the lung which may give rise to lung cancer. A clear relationship has been shown between the frequency of such cancers in uranium miners, in excess of the normal expectation, and the average radon concentration in the mines in which they had worked. The frequency of such tumours thus depends upon the conditions in the mines involved, and probably also on the smoking habits of the miners concerned [8].

66. The survey indicates an excess death rate from lung cancer in uranium miners of about 15 deaths per 10,000 man-years of mining. This figure certainly over-estimates the hazard of present uranium mining, since the tumours recorded develop and are detected many years after the radiation exposure which caused them, and mining conditions and the ventilation of mines have been improving progressively. The average rate following prolonged work at present recommended levels, which are being achieved in many mines, would probably be about one-tenth the rate quoted above (with a rate of 1.5 excess deaths per year per 10,000 miners after an average of 20 years exposure at 4 "working level months" of radon concentrations per year*).

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*The "working level" refers to a defined concentration of radon in the atmosphere of the mine.

67. External exposure from radioactive materials in rock may involve doses to body tissues as a whole of the order of 0.5 rem per year. If it is assumed that 200 miners are involved in the supply of uranium ore for a reactor of 1000 MW(e) output, an annual collective dose of 100 man.rem, (or 0.1 man.rem/MW(e)y), results from this source.

68. No direct exposure of members of the general population is to be expected. The "tailing" from mine workings contain uranium and radium and will release small amounts of radon, but these deposits are confined to the immediate vicinity of mines, and measurements in mining communities and areas are in the same general range as those in non-mining areas [1].

69. Accidental fatality rates in uranium mines of about 15 deaths per year per 10,000 miners were found in the U.S. [8]. On this basis, fatalities would average about 0.3 deaths per year corresponding to a 1000 MW(e) output.

70. It may be noted that estimates both of radiation doses and of accidental deaths would be substantially lower in opencast rather than deep uranium mines.

3. Milling and processing of ores

71. The milling and processing of ores involves the crushing of the ore and the separation of the uranium from the accompanying material, which includes radium and radon. The "tailings" of separated material are normally piled in the immediate vicinity of the mill and are considered unlikely to contribute to exposure, either by release of dissolved radioactivity into water supplies or of radon to air, unless buildings are located directly over these tailings. Measurements at both active and disused mine sites, with covered or with uncovered tailings, have indicated that significant exposure of the public from these sources is unlikely, radon concentrations and external gamma radiation measurements being at normal background levels except immediately over the deposits [1].

72. The occupational exposure of mill workers does not appear to have been widely studied and some exposure to radon or to radium may occur. Neither of these radionuclides gives rise to substantial whole body radiation, or to a genetically significant dose within the population, since the radiation from them is largely confined to lung and to bone tissues respectively. Uranium itself is little absorbed from the gut and is of low radiation toxicity, and so is most unlikely to contribute materially to genetically significant radiation.

4. Fabrication of fuel elements

73. In the fabrication of uranium fuel elements, there is rather efficient conservation of the uranium and no appreciable discharges giving rise to population exposures are to be expected. Occupational radiation exposures are believed to be low, and in any case do not involve significant whole body radiation. This holds also for any fuel enrichment by increase of the proportion of uranium 235 in fuel, since this material has the same chemical and metabolic properties as other forms of uranium.

74. With plutonium fuels for future fast reactors, problems may arise in regard to local tissue irradiation if plutonium containment is inadequate at this stage, although again without whole body exposure or appreciable doses of genetic significance, since inhaled plutonium in the insoluble form that is likely at this stage is arrested in lungs or their lymph nodes, and ingested plutonium is not absorbed appreciably from the gut. Local tissue irradiation is unlikely to be significant at this stage.

5. Reactor operation: occupational exposures

75. External irradiation of workers results in part from fission products formed and retained within the reactor system, and in part from radioactivity induced by neutron irradiation of reactor components and of materials circulating in the coolant liquid or gas. The total exposure received in these ways by reactor staff is monitored by the measuring devices worn by each exposed worker to confirm that maximum permissible exposures are not exceeded. These measurements allow an estimate of the dose involved, although this may give an over-estimate, since, for protection purposes, it is sometimes assumed as a precaution that film badges showing no detectable exposure have been exposed at the lower limit of detection. Alternatively, some readings may under-estimate the dose received if the device is not worn at the site of maximum exposure.

76. Ample data are available from which to estimate the normal amount of exposure. UNSCEAR published information in 1972 [3] on the total of all external radiation doses received by the staff of 20 reactors or groups of reactors of 6 countries and of 5 different types. In each case values were obtained for the mean dose and the number of staff involved for the period under review - usually for years during the 1960's, and also for the electrical output of the reactors during the corresponding periods. The collective exposure of staff involved in obtaining this output was expressed as the product of mean dose and numbers exposed. In this way estimates were made of the cost in radiation exposure of staff of a known electrical output from the reactors concerned. These estimates, expressed as man rems per megawatt year of electrical output (man.rem per MW(e)y) showed considerable uniformity despite the variation in type and age of reactors, half of all the 20 estimates lying between (quartile) values of 0.45 and 1.5 man.rem/MW(e)y, the median value being 0.8 man.rem/MW(e)y.

77. Further studies [9, 10] show some variation of collective dose per unit output for different types of reactor. For pressurised water reactors an average of about 0.8 man.rem/MW(e)y is received, largely during fuel replacements and repairs rather than in routine maintenance [9]. For boiling water reactors the average is rather higher at about 1.5, this figure rising somewhat with age of the reactor. Murphy [10] recorded collective occupational doses for boiling water and pressurised water reactors of 0.6 and 1.0 man.rem per MW(e) installed capacity and these figures should be about doubled for generated power. For heavy water reactors the external radiation is low at about 0.5 man.rem/MW(e)y, but some internal radiation from tritium occurs, values in early and late types noted by UNSCEAR having been 1.0 and 0.2 man.rem/MW(e)y [3]. Gas cooled reactor exposures are low at 0.7 but a contribution from tritium of up to an equal exposure may sometimes occur. Other contributions to whole body internal radiation are likely to be only slight in amount or occasional in occurrence.

78. The normal retention of fuel and of fission products within the reactor core, and of materials with induced radioactivity within the coolant, effectively prevent any substantial internal exposure from release of these materials into the working environment. Some whole body irradiation may, however, result occasionally from the release of radioactive materials from fuel elements retained in "cooling ponds" at the reactor site if defects develop in the cladding of these fuel elements. The total of such internal radiation is likely to be small.

79. A representative contribution over a range of reactors for whole body external plus internal radiation is thus in the region of 2 man.rem/MW(e)y, probably with variations from 0.5 to 2.5 (Table 3).

6. Reprocessing plants: occupational exposures

80. The reprocessing of nuclear fuels, to separate unused fuel and generated plutonium from wastes, involves exposure of staff to external radiation and possibilities of occasional internal contamination with plutonium or with other activation or fission products.

81. For external radiation, it is less easy to obtain reliable estimates of average rates of exposure than in the case of reactor staffs. A single reprocessing plant deals with spent fuel elements from many reactors, and it is not always easy to relate the total exposures (man.rem to staff) to the reprocessing load that corresponds to a given power production.

82. An estimate for the United Kingdom in 1968/69 [3], however, takes account of the mean doses received by staff in reprocessing the fuel arising from reactors having a known electrical output during the corresponding period of time. Expressed again as a product of mean dose and number of staff involved, the available data indicate that the total cost of nuclear power production in the external exposure of staff from reprocessing was 1.6 man.rem per megawatt year of electrical power developed by operation of gas cooled reactors.

83. The prevention of internal radiation exposure is more difficult during the reprocessing of fuel than in reactor operation, and incorporation of plutonium or other radionuclides into the body may sometimes occur although not ordinarily at levels exceeding the limits regarded as occupationally permissible. The average of such occasional internal exposures, in relation to these limits, is likely to be considerably less than that from external irradiation, which therefore remains the main contributor to occupational exposure. An average of about 2 man.rem/MW(e)y can be taken to cover the observed whole body radiation from external sources and any contamination with tritium or other radionuclides involving exposure of the whole body internally.

84. The death rate from accidental injury appears to be low in reactor operations as a whole relative to those in most industrial processes and rates in the region of 0.2 per 10,000 workers per year have been observed. This rate has been assumed both for reactor and reprocessing staff and would imply a total of the order of 0.04 deaths per year from accidental causes associated with 1000 MW(e)y.

7. Transportation and other fuel operations

85. In the transportation of reactor fuel and in all other steps in the processing of fuel, Hub and Schlenker [11] have estimated further minor contributions - equivalent to about 0.03 and 0.005 man.rem/MW(e)y for occupational exposures involved in transport and other steps respectively; and the same authors add about 0.005 for general population exposures during transportation.

8. Waste disposal from reactors

86. The disposal of wastes from reactors in general is likely to involve doses of radiation to the public which are too low to be measured directly and can in most cases only be estimated from assumed "models" of the distribution followed by releases of radionuclides in air or water. Moreover, to ensure compliance with national regulations, the models used are commonly such as to estimate the maximum possible doses rather than necessarily the most likely doses that will be received. Many studies, therefore, give upper estimates of population exposure from waste disposal. For our present purposes, however, this is acceptable since the total whole body or genetically significant exposures from waste disposal prove

in general to be substantially smaller, for a given power production, than those already noted as entailed in the exposure of staff at reactors and at reprocessing plants. Little inaccuracy is introduced therefore by the assumption of moderate over-estimates of these values.

87. The disposal of liquid wastes is normally controlled so as to reduce population exposure as much as is practicable, and in any case to ensure that no single group of members of the general population can receive, from all components of any discharge, an annual exposure as great as 0.5 rem per year of whole body radiation [12]. In fact, since this level of 0.5 rem per year is recommended as the limit for any such group from all forms of radiation exposure (apart from that from natural sources and from any necessary medical investigation or treatment), the maximum exposures permitted from any waste disposal are ordinarily held to a small fraction of this limit. Thus for example, the liquid discharges from reactors in the U.K. in 1971 [13] were controlled so that the maximum estimated exposure of any population group was less than 0.1% of the limit for 6 of the reactors or reactor groups, 0.3% in the seventh and 5% in the eighth.

88. In each case the estimates were made by tracing the fate of each major radioactive component of the discharge through the likely food chains or other pathways along which it might be distributed, to detect and evaluate any human exposure that might ultimately result from its circulation through the biosphere. Estimates were then made of the consequent radiation dose which any group of the population might receive, and the likely or maximum numbers of people who might receive it.

89. The total collective doses for all liquid discharges from nuclear reactors in 1971, as estimated in this way, did not exceed 3 man.rem. Since this corresponded with a nuclear power production of about 3000 MW(e) the maximum exposure rate from liquid discharges from reactors was 0.001 man.rem/MW(e)y [13], a figure which should be about doubled to allow for future dose commitment. Although this value is likely to vary substantially with reactor type, waste management procedures and the uses that are made of the water systems into which these liquid wastes are discharged, this type of release seems clearly unlikely to make more than a minor contribution to total exposure from nuclear power programmes.

90. Various radioactive gases are formed during the operation of nuclear reactors, partly as fission products and partly by neutron activation. Many of these gases have short radioactive half-lives, so that the total activity released depends upon the type of reactor and any system which it incorporates to delay the discharge of such gases until decay has occurred. Gas-cooled reactors discharge mainly argon 41, which has a half period of only 1.8 hours, while for pressurised water reactors xenon 133 of half period 5.3 days predominates in importance. Boiling water reactors on the other hand, discharge short-lived isotopes of krypton and xenon. It is not possible to generalise, therefore, either about the area surrounding, or downwind of, the reactor within which exposures will occur, or about the total dose within this area. The collective dose to populations within 80 km of boiling water reactors of modern design, which will include the greater part of the total exposure, is estimated to average about 0.02 man.rem/MW(e)y [3]. The release of argon 41 from gas cooled reactors involves an estimated total collective dose of 0.04 man.rem/MW(e)y [14]. For pressurised water reactors the dose to 80 km has been estimated to entail about 0.01 man.rem/MW(e)y and, as judged by the probable fall-off of collective dose from xenon 133 with distance [14], the total global dose is not likely to exceed 0.1 man.rem/MW(e)y. Estimates of dose to local populations depend also upon the postulation of particular distributions of the direction and speed of winds, the height of reactor

stacks, and the disposition of population densities round the reactor site. A typical contribution to population exposures from the release of such gaseous wastes from reactors would appear however to be in the region of 0.1 man.rem/MW(e)y.

91. With appropriate techniques of disposal it is to be expected that population exposure from solid waste would be minimal.

9. Waste disposal from reprocessing plants

92. The disposal of liquid wastes from reprocessing plants is normally controlled according to the same criteria as for reactors. In the 1971 U.K. survey discussed above [13], the total discharge was estimated to give rise to up to 100 man.rem from one source and to less than 0.1 man.rem from each of the two others. Since the period during which these observations were made corresponds to the reprocessing of fuel arising from a production probably of rather over 2000 MW(e)y, this exposure is equivalent to about 0.05 man.rem/MW(e)y and this figure is doubled in Table 3 (page 23) to allow for future dose commitment.

93. Gaseous wastes involve the release of krypton 85 as the main inert gas responsible for whole body exposure. Beninson [15] has recently estimated that global exposures of 0.2 and 0.1 man.rem per MW(e)y will result from krypton 85 produced by thermal and fast reactors respectively. Bryant [14] has related the sites of exposure to the global distribution of population and reaches a somewhat lower estimate corresponding to about 0.15 man.rem/MW(e)y from thermal reactors in the U.K.

94. Rather lower exposures are expected to result from releases of tritium during reprocessing of fuel and Beninson estimates global collective doses of 0.02 and 0.04 man.rem/MW(e)y from thermal and fast reactors respectively [15].

95. Whole body exposures resulting from all such gaseous releases from reprocessing plants may thus be estimated as about 0.3 man.rem/MW(e)y. Partial body exposures are likely to be considerably lower, since the high activity of the short-lived iodines, including particularly iodine 131 initially present in the fuel, are largely eliminated by allowing time for radioactive decay before reprocessing. The low activities of the very long half-lived iodine 129 contribute very small annual thyroid doses and could if necessary be largely removed by chemical separation methods.

96. Small quantities of the radioactive form of carbon, C-14, are formed in reactors by the effect of neutrons from the reactor core on atoms of nitrogen, oxygen and carbon in reactor materials. Although the rate at which this radionuclide is formed and released is lower by 3 or 4 orders of magnitude than for other activation products such as tritium or krypton, its very long half-life and its long circulation in the biosphere will cause it to accumulate slowly and cause irradiation at very low dose rates for long periods of time. The genetically significant contribution to the collective dose commitment for the world population can be estimated on the basis of circulation of carbon - containing compounds in the biosphere and in the seas, and their entry into human tissues. With an output of 6 Ci of C-14 corresponding to 1000 MW(e) per year the collective dose commitment may be estimated [16, 17] as of about 0.05 man.rem per MW(e)y during 30 years, about twice this as integrated over 500 years, and of the order of 1 man.rem per MW(e)y over the whole of future time [16].

97. It is arguable what value should be entered as the contribution from reactor discharges in current or projected power production, but the maximum figure, of 1 man.rem, has been used for

the purpose of these estimates. Releases from reprocessing plants will depend to a considerable extent on the measure used from the removal of carbon compounds from discharges.

C. EXPOSURE FROM ACCIDENTAL DISCHARGES

98. In trying to evaluate the impact of any possible accident, and the contribution of accidental releases to average population exposures, it is obviously necessary to make some estimate of the likelihood of accidents of differing magnitude. Clearly these estimates must be predictive, and based as far as possible on available knowledge or estimates of the failure rate of individual reactor components, and the consequent probability of simultaneous or successive combined failures of multiple or supposedly independent safety mechanisms. The most detailed study of this type is that directed by Rasmussen, in which a very careful examination was made of possible causes of failure /̲18̲7. It is inevitable that predictive analyses of this type will only evaluate modes of failure which have been foreseen or identified as capable of occurring, and accidents tend to arise through unpredicted combinations of circumstances. Some confidence in these and similar studies, can, however, be derived from their elaborate scrutiny of possible sources of failure of components alone or in a very wide range of combinations, and from the considerable practical experience already accumulated in reactor operation, both as regards the frequency of isolated component failures, and in regard to the validity of multiple control and safety mechanisms.

99. It must also be admitted that a major accident, leading to a substantial release of radioactivity, having an actual probability of occurrence of 1 such accident per 1000 reactors per 100 years, would have a greater influence on policy if it occurred at the beginning than at the end of the 100 years. It remains useful, however, to obtain some perspective as to whether, in the long run, the occurrence of accidental releases is likely to involve a greater or less average population exposure than the routine operation of reactors.

100. The Rasmussen draft report /̲18̲7 derives estimates of the total exposure (man.rem) for a series of accidents of varying estimated probabilities of occurrence - as calculated for population distributions and meteorological conditions applicable to the United States. These correspond to an averaged annual exposure from all accidental releases of about 25 man.rem for light water reactors.

101. Taking a load factor of 0.7 (700 MW(e)y produced) and assuming similar population and meteorological conditions, accidental releases could thus add about 0.05 man.rem/MW(e)y on average.

D. DECOMMISSIONING OF NUCLEAR PLANTS

102. Some radiation exposure of staff may be expected during the dismantling of decommissioning of reactors, but no experience is yet available on the extent of such exposure. It is difficult to believe that, as averaged over the life of the reactor, such exposure would make any substantial contribution to the total estimate of dose commitment.

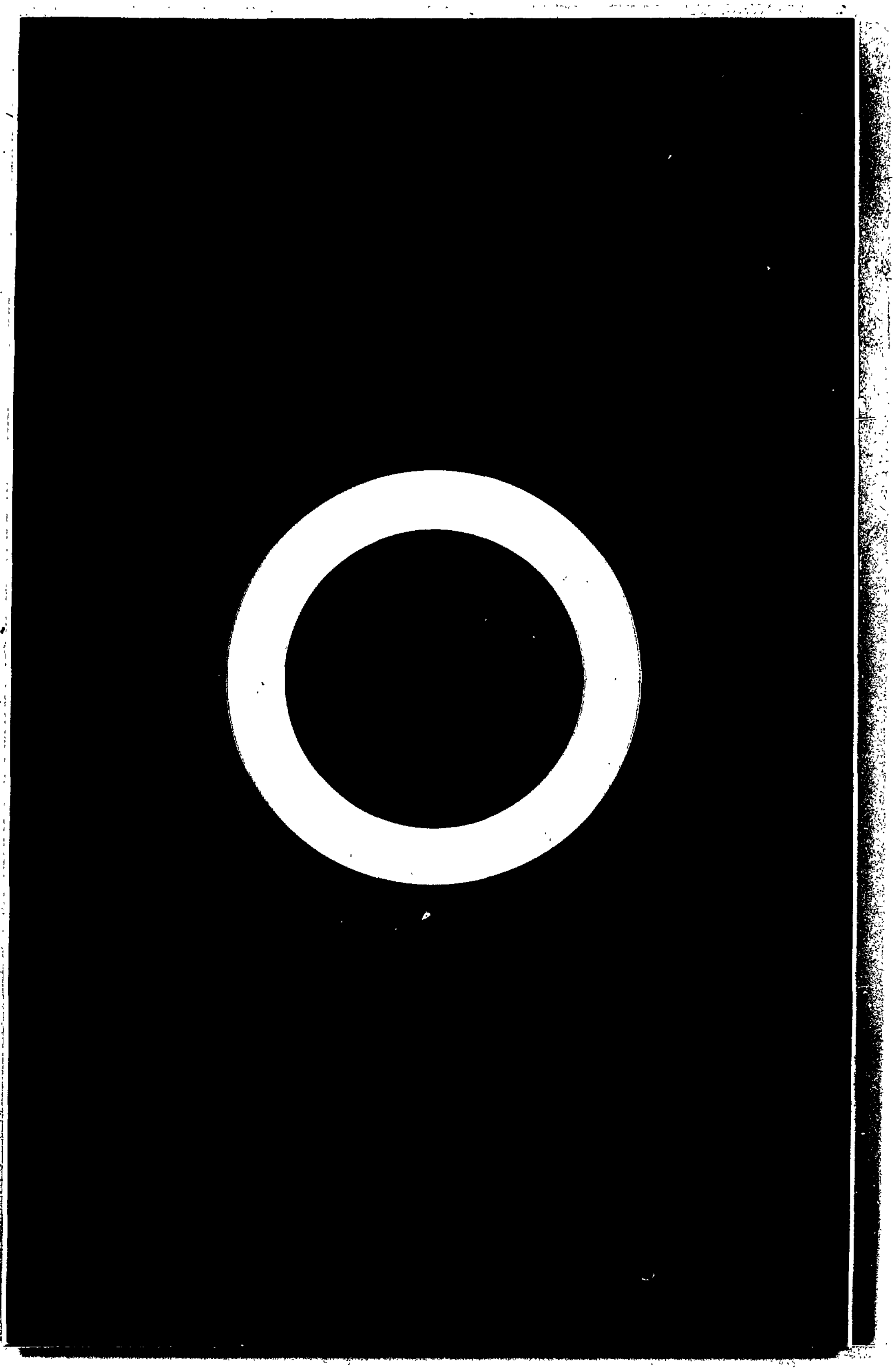
E. TOTAL EXPOSURE FROM NUCLEAR POWER PROGRAMMES

103. Summarising the dose estimates from nuclear power production, therefore, it seems clear that, although various types of partial body exposure occur and are of the greatest importance from the point of view of maintenance of health protection, particularly for those occupationally exposed, the major sources of exposure involve whole body irradiation. Of these, the main contributors to the whole population average exposure derive from the occupational exposure of staff in reactors and in reprocessing plants, even though the individual doses of most members of these staffs are maintained at levels well below those regarded as occupationally permissible. The slow release of carbon 14 contributes substantially to doses delivered over very long periods of time.

104. An approximate estimate of the contributions from a nuclear power programme to the whole body irradiation of populations can be summarised as in Table 3 (page 23).

105. An average power consumption of 1 kilowatt (electric) per head of population from nuclear sources would involve the generation of 1000 MW(e) per million of population, and therefore a collective dose of about 6000 man.rem of whole body radiation. This would result in an average exposure of 6 mrem, adding to present exposures from natural sources of 100 mrem and from all other sources of about 40 mrem. The genetically significant component of this increase would be smaller, since part of the irradiation of working or general populations would be delivered to those who were older than the age of 40 after which the probabilities of subsequent parenthood become small on average. Allowing for the likely age structure and the variation of parenthood with age in these populations, the average added genetically significant dose will be about 4 mrem. These estimates assume a uniform rate of nuclear power production throughout world populations, since some exposures from waste disposal are received at a distance from the vicinity of installations emitting them. Except for the long-term commitment from carbon 14 however, these contributions do not appreciably affect the total estimate. If the collective dose commitment were averaged only over the next 30 years the estimate would be somewhat lower by omission of the later contributions from carbon 14 and would be of about 5 mrem and 3 mrem per year for whole body and for genetically significant mean doses respectively.

106. Such estimates are clearly only approximate, since they depend critically on reactor type, size of reactor and reprocessing staffs, and the exposures that they may receive; and to a lesser extent on assumptions as to waste disposal practices, population densities and the distribution models assumed. They give a basis however for reviewing the possible biological cost in harm from the added exposures.



IV. ESTIMATED FREQUENCY OF HARMFUL EFFECTS FROM NUCLEAR POWER PROGRAMMES

107. In estimating the costs in human harm of power production by nuclear energy, we need to consider four components.

i) The frequency with which diseases, and particularly fatal malignant diseases, are induced in the various population groups in which there is radiation exposure of the whole body.

ii) The frequency of genetic abnormalities caused by the genetically significant component of these irradiations.

iii) The additional frequency of diseases induced by local irradiation of parts of the body only, in various groups so exposed.

iv) The frequency of accidental injury and disease, and particularly of accidental death, involved at all stages of the power production process.

108. This will give an estimate of the total harm or "detriment" to be expected, for example, for one year in a million people deriving 1 kilowatt of electrical power per head from nuclear energy. This estimate can then be compared with the detriment to be expected from a comparable energy production by alternative means and also with that from lack of such energy production.

A. FREQUENCY OF RADIATION INDUCED DISEASE FROM WHOLE BODY IRRADIATION

109. Several major studies have given estimates of the frequency with which fatal malignant disease, including leukaemia, is induced in groups of people in which all or much of the body has been exposed to relatively high radiation doses, usually approaching or exceeding 100 rem. These groups include the survivors of radiation from the atomic bombs in Hiroshima and Nagasaki, patients treated for spinal or other diseases involving extensive body exposure, or - at much lower doses - children irradiated before birth in the course of diagnostic pelvic X-rays to their mothers. The estimated frequencies of all fatal malignancies from such studies are supplemented by evidence as to the frequencies of various malignancies under conditions in which the irradiation involved only or mainly the organ from which the particular malignancies arose. Further support for the estimates is obtained from studies in which the radiation dose was not known, but in which data were obtainable on the ratio between the total excess of fatal malignant tumours and the total excess of cases of leukaemia, for which the induction rate per unit dose can be inferred from other surveys.

110. Many uncertainties are involved in certain aspects of these studies - the number of deaths to be expected at longer intervals after the exposure than had been studied, the amounts of radiation exposure or the relative importance of different types of radiation, the significance of age at the time of exposure, and the

validity of the various unexposed groups examined to estimate the frequency of the relevant diseases in the absence of radiation. Despite these uncertainties, reasonably consistent estimates have been made by a number of authorities.

111. UNSCEAR [19] reached an estimate of between 115 and 140 fatal malignancies per million exposed per rem. The "Beir" report of the U.S. National Academy of Sciences [20] gives separate estimates for populations of working ages (from 20 to 65) and of all ages. Their estimates would correspond to a total of 93 to 328 fatal malignancies per million per rem for an exposure of which 75% was to working populations and 25% to general populations, as in the present survey. Recent discussion of newer information available since both these reports has given estimates in the range of 100 to 200 fatal malignancies per million per year. A central value of about 150 per million per year would thus be consistent with most likely estimates from these and other sources. To this total would be added a lesser number, perhaps of the order of 100 per million per rem, of thyroid or skin tumours fully removable by operation; and probably very few illnesses of any other type, or injuries to embryos, attributable to radiation at the dose levels concerned.

112. Within this group of harmful effects, therefore, a mean dose rate of 6 mrem per year to a million people might give rise to of the order of 0.9 fatal and 0.6 cureable malignant tumours annually. These may be over-estimated unless the frequency of tumours per unit of dose remains proportional to the amount of radiation exposure both at high and at low doses.

B. FREQUENCY OF GENETIC ABNORMALITIES

113. Estimates can be derived both from the UNSCEAR and from the BEIR reports of the frequency of substantial genetic abnormalities that would occur annually in liveborn children in a population exposed continuously to a genetically significant dose of 1 rem per year. On a basis of evidence as to the radiation dose (of 100 rem) that would double the natural rate, UNSCEAR estimated this figure as 300. Alternatively, by summating the frequencies from different types of mutational or chromosomal abnormality, the same central value of 300 is obtained, although with limits of uncertainty that would raise or lower the estimate by a factor of about 5 [19]. The corresponding estimate derivable from the BEIR report is again about equal at 300, with limits greater or less by a factor of 6 [20]. By each analysis, the numbers appearing within the first generation (30 years) after the start of the radiation would be about 50 (per million of population per rem of genetically significant dose).

114. A continuing genetically significant exposure of 4 mrem per year from nuclear power production would thus be expected to give rise to about 0.2 defects per year during the first generation (or rather less, since the carbon 14 contribution to dose would still be small within this generation) rising to 1.2 defects per year after many generations. These estimates might be too high or too low by a factor of 5 or 6.

C. FREQUENCY OF ADDITIONAL DISEASES INDUCED BY LOCAL IRRADIATION

115. The irradiation of lung tissues by uranium miners is likely to constitute a significant contribution in this category. If all mine ventilation was adequate to reduce radiation concentrations to the recommended maximum (of "one-third of a working level"),

the excess mortality from lung cancer should not exceed 150 deaths per million per year. The practical difficulty in reaching these levels uniformly throughout all mines probably implies however that a rather higher risk would apply.

116. The uranium oxide requirement for a 1000 MW(e) station is of several hundred tons of ore per year, and the number of miners at risk would depend critically upon the degree of mechanisation used as well as on the proportion of ore obtained from opencast mines in which radon levels should always be much lower. If 200 miners were working in deep mines, a total of 0.03 lung cancers would be expected per year or perhaps up to 0.05 allowing for the probability of excess radon concentrations in some mines, and for longer periods of mining than the 20 years referred to above.

117. Any further contribution from radioactive intakes in reactor and reprocessing staffs seems unlikely to increase this figure substantially. Thus, if 2000 staff were involved in reactor and reprocessing operations for a 1000 MW(e) output, 0.1 fatal malignancies would only occur per year if all staff sustained continuously an average of one-tenth the maximum permissible levels of partial body internal irradiation, and such an average level is improbable.

118. Partial body irradiation of members of the general public arises to a limited extent from both liquid and gaseous discharges. On the basis of the UK analysis [13] most of the liquid discharges involve either external irradiation or internal exposure from radioisotopes of caesium in fish, both giving whole body irradiation of which account has been taken already. Traces of cobalt 58 and 60 and of manganese 54 in fish add little to these doses. From the estimated maximum doses [13] and the population exposed [21] the consumption of laverbread containing a form of seaweed may have involved up to a tenth of a man.rem per MW(e)y to the intestine [21] and about the same to bone. In gaseous discharges krypton 85 will deliver a dose to the skin from beta radiation in addition to that to the whole body, amounting to about 5 man.rem per MW(e)y [16]. The long half-lived iodine 129 is released in very low activities but will accumulate slowly and irradiate the thyroid gland in which iodine isotopes become concentrated. As in the case of carbon 14, a maximum estimate may be derived by considering the collective dose commitment as integrated over 500 years, and, if all iodine 129 formed in the reactors were released, this collective dose would reach about 0.5 man.rem/MW(e)y [15].

119. Relating these exposures of the general population to the hazard assumed for the various tissues irradiated singly, it appears that these contributions would add of the order of 0.05 fatal and 0.5 operable cancers* [per year per 1000 MW(e)] to the total of 0.15 or fewer fatal cancers arising from occupational exposure to partial body radiation. These estimates are necessarily very approximate, but indicate that the risk from partial body irradiation is likely to be rather less for operable tumours, and considerably less for fatal tumours, than are those from whole body radiation.

D. OCCUPATIONAL ACCIDENTS

120. Accidental deaths can be estimated very approximately on the following basis. The heavy constructional work entailed in the building of installations is likely to involve a fatality rate in the region of 8 per 10,000 per year. With a labour force of 1000 for 5 years, this would indicate the likelihood of about 4 deaths for reactor construction (and there is some direct evidence that an

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*Of skin and thyroid.

average of 4 or 5 such deaths do in fact occur). Assuming an operating life of at least 20 or 25 years indicates an annual rate for reactor construction of about 0.2 deaths, or say 0.25 to include the smaller numbers of reprocessing plants.

121. Assuming that 200 miners are involved in deep uranium mining with a fatal accident rate of 15 per 10,000 per year [8], a further 0.3 death per year should be added from this source. In the relatively small staffs involved in milling, 0.1 deaths per year have been assumed.

122. Deaths from occupational diseases are likely to be less than in coal mining and should not raise this figure to more than about 0.4. (Estimates of deaths directly attributable to occupational causes in coal mining vary very considerably [22], but recent statistics from the Federal Republic of Germany [23] attribute 75 deaths to occupational diseases in coal miners as compared with 160 deaths during the same period from accidental fatalities).

123. As discussed above, transportation accidents will depend very much on loads and distances involved, but a low figure of 0.002 deaths per year has been suggested [11] from transportation connected with a 1000 MW(e) plant in the United States. A transport staff of 50, each driving 1000 km per week, with a risk of fatality, as for public service vehicles, of 0.14 per million km [24], would entail a similar figure of 0.003 deaths per year. Accidents to reactor and reprocessing staffs should add less than 0.05 deaths per year.

124. To this total of rather under 0.8 fatalities per year must be added a number of non-fatal accidents and illnesses that are likely to arise, mainly from the construction and mining phase of the programme. Data for the U.S. [7] show about 88 and 70 "disabling accidents" for every one accidental death in constructional work and mining respectively. An annual number of 22 + 21 = 43 such accidents might thus be expected. Non-fatal illnesses are not likely to increase this total substantially, and indeed the total for all non-fatal disabilities have been estimated [11] as 5 to 25 per year per 1000 MW(e). An approximate figure of 50 disabilities may thus be added to that of 0.8 fatalities.

E. TOTAL ESTIMATED HARM FROM NUCLEAR POWER PROGRAMMES

125. These, necessarily very approximate, estimates of harm would thus suggest that the supply of a year's needs of 1 million people at 1 kW(e) each from nuclear power might involve in the region of 1 death from malignant disease and an equal number of cases curable by operation, with about 1 fatal and 50 other disabling accidents and, after some generations of operation, of the order of 1 to 1.5 genetic defects of greater or less severity, per year.

V. HEALTH HAZARDS INVOLVED IN POWER PRODUCTION

A. COMPARISON WITH HEALTH HAZARDS FROM ALTERNATIVE MEANS OF POWER PRODUCTION

126. In making a choice between alternative methods of power production, considerations of occupational and environmental health clearly form only one, even if an important, factor. Many other factors such as cost, availability, needs of employment and facilities for training or conduct of the industry may be dominant. It is particularly important, however, that the effects upon health of procedures involving radiation exposure should be compared, as objectively and numerically as possible, with those involved in the development of alternative sources of power. This need is the more urgent since the types of harm that may be induced by radiation, and the frequency with which they may be so induced, are necessarily less familiar than in the case of other hazards and pollutants associated with existing methods of power production. Moreover, since no increase of malignant or other disease has been detected in any present occupation involving radiation exposure, with the one exception of uranium mining, estimates of harm must necessarily still be based on predictions of possible frequencies of harm rather than on observations of actual frequencies.

127. The difference in type of harm, with the induction of malignant disease and of genetic injury as compared with accidental deaths and injuries, is understandably thought of as giving a worse character to the hazards of nuclear as compared with other forms of power production, and this increases the need for a proper perspective as to the frequency with which these effects might occur. In fact, however, the induction of malignant disease by chemical factors in the working environment is, unfortunately, becoming recognised in a number of industries or production processes, and carcinogenic chemicals are commonly also mutagenic. Indeed, the risks of fatal malignancies involved in some forms of industrial exposure to chemical agents have been shown to involve up to 10 to 30 deaths per 10,000 workers per year [25], as compared with a probably maximum estimate of less than 1 per 10,000 per year for industries involving radiation exposure.

128. Several studies have been made of the frequency of injuries or fatalities associated with a given electrical power production by conventional means. Thus, for example, Hamilton and Morris [26] made estimates for power production by coal, oil and gas; and Hub and Schlenker have published a similar analysis [11]. Such estimates necessarily depend on regional conditions of population density, observed fatal and other accident or illness rates, and distances over which materials require to be transported. It is important therefore that similar comparative studies should be made for areas in which the development of nuclear power programmes is being considered. As an approximate basis for comparison, however, the general results of existing reviews are of value.

129. For a year's production of 1000 MW(e) by coal, Hamilton and Morris [26] estimate the occurrence of 0.6 deaths in mining, 0.04 in processing and 1.2 in transport of fuel. For oil, their corresponding estimates of occupational fatalities are 0.1 for extraction, 1.0 during refining and 0.03 in transportation. For gas, extraction involves 0.1 deaths, processing involves a negligible fatal hazard and transportation accounts for 0.03 deaths.

130. When they include the health hazard to the general population from air pollution - specifically from sulphur dioxide, suspended particulates, polycyclic hydrocarbons, oxides of nitrogen, ozone and other secondary products - their estimates of expected mortality, to an 80 km radius from a 1000 MW(e) plant, are of 45 deaths annually from coal, 1.5 from oil and 0.15 from gas (with 1.0 from nuclear power).

131. Hubb and Schlenker [11] estimate that one year's operation of a 1000 MW(e) plant, including fuel production and transportation, would involve a total number of deaths from occupational causes of 1.1 for coal, and 0.2 for oil. To the general public, they add 0.6 during transportation for coal. Their estimate of environmental hazards would, with a population density of 100 per sq.km, involve from 0.4 to 2 deaths per year from either coal or oil within a distance of 80 km.

B. BASIC APPROACH TO DECISIONS ON POWER PRODUCTION

132. In taking any decision, it is of value to be able to compare the relative costs and benefits of the alternatives. This is ordinarily very difficult, owing to problems in evaluating the benefits in any objective way, and in relating them in any comparable numerical terms with the costs.

133. In making a choice between alternative sources of power the problem is simpler since, in large measure, the benefit of available power is equal in each case and the question largely resolves into a comparison of costs, of which health must be a major one. It is impossible to compare directly the importance, to the public or to the worker, of a given number of deaths from accidental causes with an equal number from induced disease, or of defects in later generations, and factors of anxiety and public evaluation will attach very varying weight to different effects. It must remain important, however, to have an assessment of the likely frequency of various effects, and to make decisions in the light of such frequencies rather than merely in the fear that certain types of effect may occur. In this sense the hazards involved in radiation exposure need to be reviewed in just the same way as those from any other form of chemical or physical agents, some of which in any case have similar types of effect. It is however evident that, since any radiation exposure may cause harmful effects, all unnecessary exposure should be avoided and - as for any other hazardous agent - any exposure should be justified by the purpose for which it is used.

134. A further factor which simplifies decisions relating to radiation exposure is that, at the dose levels involved in the present survey, the hazards resulting from such exposures are likely to be simply proportional to the size of the dose received. This implies that the harm to be expected from each of a number of procedures involving radiation exposure can be considered separately and the contribution of one source of exposure - for example, from radiology - does not alter the estimate of risk from another. Each procedure involving radiation exposure can therefore be evaluated independently, so that it can be ensured that the hazard involved is justified, or more than justified, by the needs for the procedure. In this way, the total radiation exposure of the population from all

sources is to be justified by the needs for each source, rather than by any allocation of a fixed total harm between competing requirements regardless of the necessity for each. What requires to be minimised is the total risk to the population, not the risk from individual types of hazard considered independently. Decisions on power production can then be taken in the light of total hazards from alternative sources, as well as of the hazards from failure to develop any such source.

C. GENERAL CONCLUSIONS

135. The analysis presented in this report is necessarily approximate, since it estimates future radiation exposures and hazards on the basis of present experience of the exposures involved in the operation of reactors and reprocessing plants, and in the disposal of gaseous and other radioactive wastes. It should, however, give an adequate basis for comparing the added radiation exposure of workers and members of the public from any extensive programme of nuclear power production, with the radiation exposures already received from natural sources and from other accepted artificial sources. It should also provide a basis for comparing the total health hazards involved in power production from nuclear sources with those incurred during equal power production by other means, so that health aspects can be taken properly into account in any decisions as to the development of additional power supplies and the sources from which they should be derived.

136. The conclusion reached in the present report is that a substantial nuclear power programme, developing 1 kilowatt of electrical power from nuclear sources per head of population, would increase the normal exposure always received by the population from natural sources by an average of about 6%. This compares with average increases in the region of 35% from radiological procedures, 6% to the present generation from the fallout from nuclear tests, and about 0.6% from other artificial sources, as discussed in Chapter II and summarised in para. 54. Figure 1 expresses diagrammatically these average doses received from the various natural and artificial sources of radiation exposure, as determined for the particular countries and conditions described in the text.

137. The value of comparing the doses of radiation received from different sources in this way is that, as described in Chapter I, the frequency of any harmful effects attributable to each source is likely to be directly proportional to the radiation doses delivered to the relevant body tissues by each such source. This relationship holds both for the frequency of malignant changes which may be induced in the individual exposed, and for that of genetic abnormalities induced in his or her descendants, as discussed in Chapter I.

138. Absolute estimates of the actual frequencies with which malignant changes might be induced by the doses of radiation received from the various sources have been derived from studies of human populations following exposure of the whole or part of the body to known doses of radiation. These estimates of the cancer or leukaemia risk per unit dose are ordinarily derived from exposure to very much higher doses than are involved in nuclear power production, since it is only following such high doses that any increase in occurrence of malignancies is detectable. In consequence it is likely that the risk from low doses is over-estimated by this procedure. The risk of genetic abnormalities is inferred from experimental studies on animals.

139. In this way, the total health costs of a nuclear power programme at any given level have been derived in Chapter IV from the estimates of the radiation doses received during each stage of

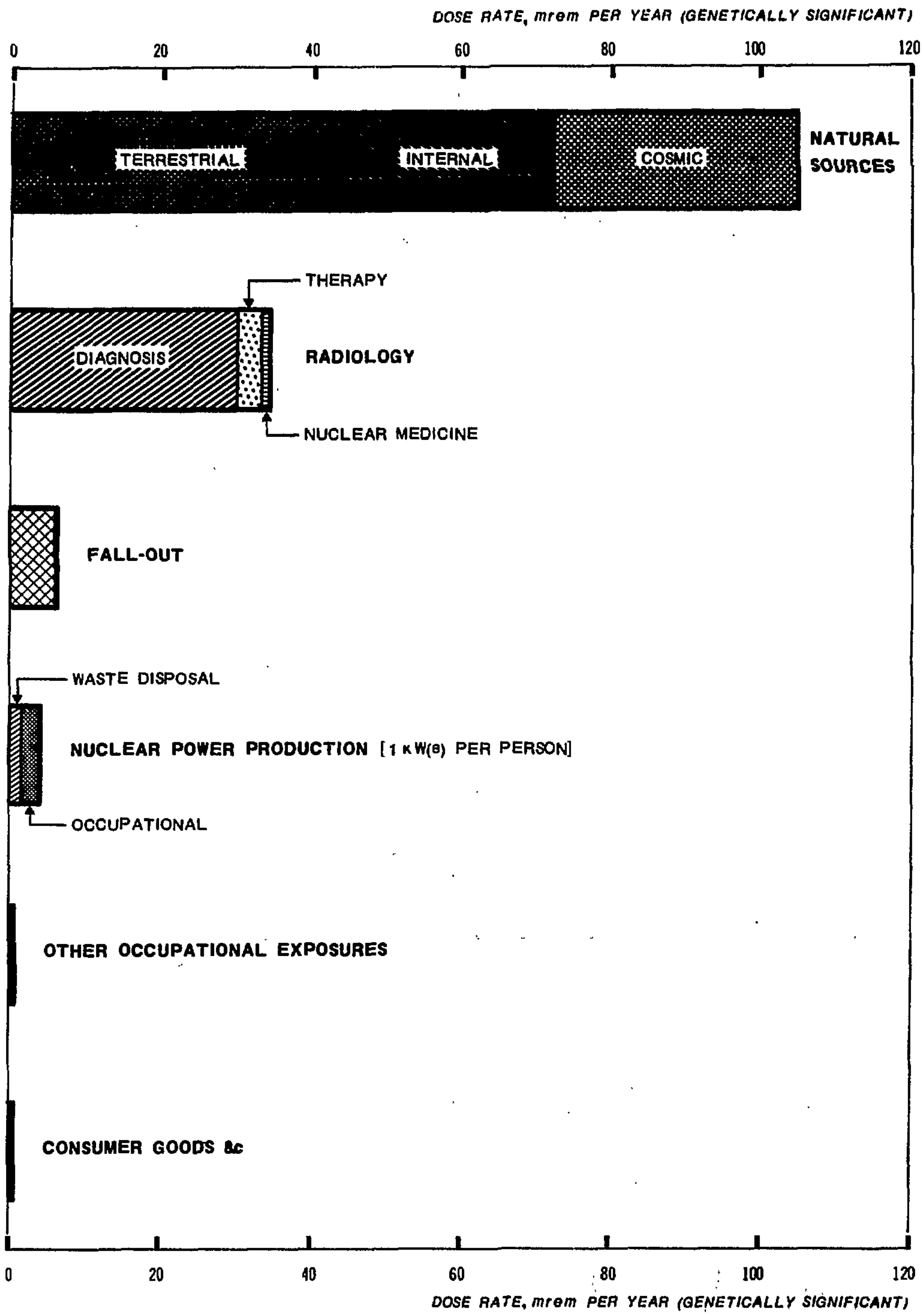

Figure 1

ANNUAL GENETICALLY SIGNIFICANT DOSE RATE, AS AVERAGED THROUGH WHOLE POPULATION

nuclear power production, from the mining of the ore to the disposal of radioactive wastes and the reprocessing of nuclear fuel. As described in Chapter III, an integral is obtained of doses received and of the number of people receiving them, both for workers in the various types of plant and for members of the general public who might be exposed to radiation from gaseous or other waste disposal or from accidental releases. Account is taken also of exposures involving part of the body or single organs only and in these cases the estimates of harm depend upon the sensitivity of the particular organs in question to cancer induction by radiation.

140. In quantitative terms, the total impact of these radiation exposures is conveniently expressed as the "collective dose" throughout the population - the size of individual doses multiplied by the number of people receiving them - resulting from a given level of nuclear power production. Table 3 gives these values - as collective doses in man.rem from each stage of the production of 1 megawatt of electrical power during one year - i.e. as man.rem/MW(e)y.

141. It is seen that, of the total of whole body exposures in the population, 4.2 man.rem/MW(e)y is incurred as the occupational exposure of workers, mainly at reactors and at reprocessing plants, the integral exposure of members of the general public being smaller at 1.5 man.rem/MW(e)y. Most types of waste disposal, including an estimated annual discharge corresponding to possible accidental releases as averaged over a period of time, amount to only 0.5 man.rem/MW(e)y, but an additional figure of 1.0 man.rem/MW(e)y is included in respect of the slow discharge of low activities of radioactive carbon - C-14 - which, because of its long persistence in the environment, is likely to cause exposure at very low rates over a very long period.

142. In estimating the frequency of genetic effects, the ages of those exposed must be taken into account. The collective dose received during occupational exposure has a smaller genetically significant component than that received by the general public, in view of the greater average age, and lower expectation of subsequent childbearing, of the former than of the latter. Of the 4.2 man.rem of genetically significant collective dose from 1 MW(e)y, 2.7 derives from occupational exposure and 1.5 from that of the public.

143. Table 3* records also the circumstances in which irradiation occurs which is limited to parts of the body or single organs, owing to the deposition or concentration of particular radioactive materials in these situations. The highest and most consistent of these exposures is likely to be that of lung tissues in uranium miners from inhaled radioactive materials. The number of lung cancers that is estimated to result from this exposure, however, makes only a minor contribution to the total harm of power production in view of the small number of miners involved in maintaining the necessary supplies of ore.

144. Table 3* also gives estimates of the number of fatal accidents that may be expected to occur during each stage of the production process, having regard to the numbers of workers likely to be engaged, and the accident statistics for the types of work involved. The largest contributions to the total of such accidental deaths are likely to arise during mining and in the construction of installations. Other non-radiation illness and accidents are also discussed in Chapter IV.

145. It thus becomes possible to estimate the total of all fatal accidents and diseases, and of major non-fatal conditions, resulting for example within 1 year in a population of 1 million people deriving 1 kilowatt per person of electrical energy from nuclear power. The estimates will necessarily depend to some extent on type of reactor, techniques of waste disposal, population density,

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* See page 23.

radiation protection practices and many other factors, as well as on the accuracy of the risk estimates of the malignant or genetic effects of radiation exposure at low doses. Under the conditions assumed in the present analysis, the stated level of power production would involve each year in the population of 1 million, about one death from malignant disease, one case of malignant disease fully curable by operation, one fatal and 50 other disabling accidents; and after some generations of operation, of the order of 1 to 1½ genetic defects of greater or less severity.

146. It is essential that such costs in health should be taken into account in decisions as to sources of increased power production, and that they should be compared with corresponding estimates of the health costs of alternative sources of power, some at least of which appear to involve very substantial health hazards of various types per unit of power produced.

147. It is to be hoped that the health aspects of alternative methods of power production can be reviewed in this way on the basis of quantitative estimates of the amount of harm that may be involved by each, and, indeed, that such estimates should be compared with an assessment of the harm that would result from failure to develop additional power by any of the available methods.

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