NOTE

The report of the Committee without its annexes appears as Official Records of the General Assembly, Thirty-seventh Session, Supplement No. 45 (A/37/45).

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Report of the United Nations Scientific Committee on the Effects of Atomic Radiation to the General Assembly

CONTENTS

I. INTRODUCTION

1. Since its establishment in 1955 the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR)[1] has reported yearly to the General Assembly and at irregular intervals has submitted more comprehensive reports with detailed scientific annexes. This is the eighth in the series of such substantive reports.[2] It consists of a summary and a main text outlining the conclusions reached in the Committee's discussions and twelve scientific annexes reviewing in considerable detail the procedures and the scientific information on which such conclusions rest.

2. Although the Committee has attempted some systematic coverage of the issues entrusted to its attention, not all sources of radiation exposure and radiation effects have been included in this report. In the light of previous work, this report deals specifically with subjects that were felt to be in need of consideration because of the development of relevant scientific knowledge. Thus, some annexes have simply been updated from the 1977 report; others have largely been reassessed after many years of development; other matters are essentially considered for the first time.

3. Following past practice, only the summary and the main text of the report are submitted to the General Assembly. The full report with scientific annexes is being made available at the same time as a separate publication[3] for wide circulation to the scientific community, which has received past reports of UNSCEAR as authoritative sources of independent information and evaluation. The Committee wishes to draw the attention of the General Assembly to the fact that separation of the main text of the report from its scientific annexes is simply for reasons of convenience. The documentary evidence given in the annexes as a basis for the Committee's conclusions is of major importance.

4. Preparation of this report took place during the twenty-seventh to the thirty-first sessions of UNSCEAR. M. Klímek (Czechoslovakia), F.E. Stieve (Federal Republic of Germany) and K. Sundaram (India) served as chairman, vice-chairman and rapporteur, respectively, at the twenty-seventh session. The same functions were performed by F.E. Stieve (Federal Republic of Germany), Z. Jaworowski (Poland) and D. Beninson (Argentina) at the twenty-eighth and twenty-ninth sessions. Finally, Z. Jaworowski (Poland), D. Beninson (Argentina) and T. Kumatori (Japan) acted as chairman, vice-chairman and rapporteur, respectively, in the course of the thirtieth and thirty-first sessions. All these sessions were held in Vienna.

5. The work of the Committee was carried out in meetings of specialist scientists who, in their capacity as official representatives or scientific advisers of national delegations, considered, discussed and amended working papers prepared by the Secretariat at the Committee's request. The names of those specialists who attended one or more of the sessions during the preparation of the report are listed in Appendix I.

6. The Committee was assisted in its work by a small scientific staff and by expert consultants appointed by the Secretary-General. While in approving the present report the Committee itself assumes full responsibility for its content, it wishes to acknowledge the assistance given by those scientists who were responsible for the preliminary review and analysis of the data. The names of those scientists and consultants are listed in Appendix II. The Committee owes much to their collaboration and technical advice.

7. Information received between 13 April 1977 and 26 March 1982 at the Committee's Secretariat from State Members of the United Nations, members of specialized agencies and of the International Atomic Energy Agency, as well as from these agencies themselves, is given in Appendix III. Information received previously has been listed in earlier reports to

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[1] The Scientific Committee was established by the General Assembly at its tenth session. The terms of reference of the Committee are set out in resolution 913 (X). The Committee was originally composed of the following Member States: Argentina, Australia, Belgium, Brazil, Canada, Czechoslovakia, Egypt, France, India, Japan, Mexico, Sweden, the Union of Soviet Socialist Republics, the United Kingdom of Great Britain and Northern Ireland and the United States of America. The membership of the Committee was subsequently enlarged by General Assembly resolution 3154 C (XXVIII) to include the following other States: Germany, Federal Republic of, Indonesia, Peru, Poland and Sudan.

[2] Previous substantive reports of the Scientific Committee to the General Assembly are to be found in: *Official Records of the General Assembly, Thirteenth Session, Supplement No. 17* (A/3838); *ibid., Seventeenth Session, Supplement No. 16* (A/5216); *ibid., Nineteenth Session Supplement No. 14* (A/5814); *ibid., Twenty-first Session, Supplement No. 14* (A/6314 and Corr. 1); *ibid., Twenty-fourth Session, Supplement No. 13* (A/7613 and Corr. 1); *ibid., Twenty-seventh Session, Supplement No. 25* (A/8725 and Corr. 1); *ibid., Thirty-second Session, Supplement No. 40* (A/32/40). These documents will be referred to in this context as the 1958, 1962, 1964, 1966, 1969, 1972 and 1977 reports, respectively. The 1972 report with appendices and scientific annexes was also made available as: *Ionizing Radiation: Levels and Effects, Volume I: Levels* (United Nations Publication, Sales No. E.72.IX.17) and *Volume II: Effects* (United Nations Publication, Sales No. E.72.IX.18). The 1977 report with appendices and scientific annexes appeared as: *Sources and Effects of Ionizing Radiation* (United Nations Publication, Sales No. E.77.IX.1).

[3] United Nations Publication, Sales No. E.82.IX.8.

the General Assembly. All these data were obtained officially by the Committee and were supplemented by, and interpreted in the light of, a large amount of information published in the open scientific literature. In a very few instances, unpublished contributions by individual scientists were also utilized or information was made available by individuals or organizations in response to specific requests by the Committee. These contributions are acknowledged with appreciation.

8. Representatives of the International Atomic Energy Agency (IAEA), the World Health Organization (WHO), the United Nations Environment Programme (UNEP), the International Commission on Radiological Protection (ICRP) and the International Commission on Radiation Units and Measurements (ICRU) attended the sessions of the Committee during the period under review. Their contribution to the discussions for the preparation of this report is gratefully acknowledged.

9. In compliance with its mandate, the Committee has formulated plans to continue its review of the radiation levels to which the world population is at present, or may in the future become, exposed and of the effects and risks that could derive from such exposures. The Committee proposes to keep under close scrutiny those areas which will emerge as meriting special attention for their scientific relevance or their practical significance. The Committee believes that such studies will also provide a significant contribution to the activities of the United Nations Environment Programme with which the Committee intends to maintain close functional relationships.

10. In the sections to follow the Committee summarizes the main conclusions reached in the present report in the light of previous substantive reports and then examines in detail the outcome of the studies that were conducted in specific areas in both the physical and biological fields.

II. SUMMARY OF THE MAIN CONCLUSIONS

11. This report has been structured in such a way that it may be read at various levels of detail and complexity. The present chapter summarizes the most important conclusions of the extensive surveys carried out in the different fields, particularly in the light of previous reports submitted to the General Assembly. The text aims at highlighting the main trends that have become apparent throughout the years in the form of overall comprehensive evaluations.

A. ASSESSMENTS OF RADIATION LEVELS AND DOSES

12. In this report, as in previous ones, the Committee has systematically reviewed all the sources of ionizing radiation that give rise to human exposure, namely, natural sources, nuclear explosions, nuclear power production, use of radiation for medical, industrial and research purposes, and radiation-emitting consumer products. Both occupational exposures (that is, the exposures incurred during the course of work) and non-occupational exposures have been considered. For each source of ionizing radiation, the results are expressed in two ways. On the one hand, results are given in terms of individual doses, which from an individual point of view show the relative importance of the type of work, the place of residence, or particular habits. On the other hand, collective doses have also been used. As these are the sum of the individual doses resulting from a given source, they provide an index of the total health impact of that source. The use of collective doses permits comparison of the impact from a wide range of dissimilar sources or practices giving rise to ionizing radiation.

13. A basic assumption was adopted by the Committee for the purpose of dose assessments at the start of its activity and is still in use at present. This is the hypothesis of direct proportionality between doses and probability of occurrence of effects (cancers or genetic disease) for the relatively low levels of dose and dose rate that are generally considered in this report. The hypothesis is meant to apply to large populations comprising individuals of both sexes and of various ages, and not to a single individual. This hypothesis is not contradicted by the large body of experimental and epidemiological data. There are reasons to believe that it does not underestimate the risk at the low doses and dose rates of interest to the Committee, and it may in fact overestimate this risk.

14. This report differs from previous reports in one important aspect. Instead of estimating the absorbed doses to only a limited number of important tissues (for example, gonads, lungs and bone marrow) the Committee now combines the doses in all organs and tissues in an expression of dose called the "effective dose equivalent" (see paragraphs 66–69) which the Committee believes to better represent the whole risk incurred by the exposed populations. As a consequence, the present assessment of the relative importance of some radioactive substances has changed in certain cases in comparison with the previous reports of the Committee.

1. Natural sources

15. The major contribution to the annual average doses received by mankind comes from natural radiation sources, which include external sources, such as cosmic rays and radioactive substances in the ground and in building materials, and internal sources resulting from the inhalation and ingestion of naturally occurring radioactive substances in air and in diet. Inhalation is now recognized to be the most important pathway, followed by external irradiation and ingestion. Most of the effective dose equivalent from inhalation is due to radon which is a radioactive noble gas often present in relatively high concentrations in indoor air.

16. Distinctive characteristics of natural irradiation are that it involves the whole population of the world and that it is and has been experienced at a relatively constant rate over a very long period of time. For these reasons, it may be used as a reference level for comparison with man-made sources of ionizing radiation.

17. The dose from natural sources of radiation received by a given individual depends upon a number of conditions, including the place of residence, the type of dwelling and the altitude. For most of the world's population, however, the range of individual doses from natural sources is considered to be rather narrow, as it probably extends only between one-half to two times the average value.

18. Nevertheless, when a separate component of the dose from natural sources is considered, it is generally found that some individuals are exposed to levels much higher than the average. Examples of such individuals are those who live in areas where the soils and rocks are rich in natural radioactive substances, those who live in buildings with high radon concentrations, those who live at high altitudes above sea level, and those who eat foodstuffs containing unusually high concentrations of radioactive substances.

19. The Committee has previously reviewed the exposures from natural sources of radiation in its 1958, 1962, 1966, 1972 and 1977 reports. Because of an increasing number of measurements, dose assessments have become increasingly accurate, particularly with respect to external irradiation. In the present report, expressing dose in terms of effective dose equivalent emphasizes the importance of the inhalation pathway; on average, about one-half the effective dose equivalent from natural sources of radiation is now calculated to be due to the presence of radon in the air inside buildings.

2. Man-made sources

20. Exposures to natural sources of radiation vary little from year to year and involve the whole population of the world to about the same extent. On

the contrary, man-made sources may vary significantly with time and the resulting exposures may differ substantially from one population group to another.

(a) *Medical irradiation*

21. At present medical irradiation ranks first in amount among the man-made sources of human exposure. Radiation is used in medicine for diagnostic purposes (e.g., x-ray or nuclear medicine examinations) and for the treatment of diseases, mainly cancers. The doses received by patients are extremely variable: from very small, as in many diagnostic examinations, to very high, such as those delivered in clinical radiotherapy. As medical exposures usually involve irradiation of limited regions of the body, it has been difficult in the past to compare them with other types of exposure. The use in this report of the effective dose equivalent is intended to diminish that difficulty.

22. Annual individual doses vary from zero, for the non-exposed patient receiving no diagnostic or therapeutic exposure, up to several tens of thousand times the annual average dose from natural sources, delivered to the treatment volume of patients undergoing radiotherapy. Under these conditions average doses are not very meaningful, although collective doses may give some indication of the impact of medical sources. In industrialized countries, the annual collective effective dose equivalents from x rays and nuclear medicine diagnostic irradiation may be in the region of one-half of the annual collective dose from natural sources. The contribution from exposure of patients for therapeutic purposes has not been estimated by the Committee. However, this component would need to be assessed differently, since it applies generally to people in later life who have a low probability of long-term or latent radiation-induced consequences due to their more limited life expectancy.

23. Data from developing countries are only now becoming available, in part as a result of collaboration with the World Health Organization. These data indicate an examination frequency about ten times lower than that in industrialized countries. Consequently, the annual collective effective dose equivalent applying to medical exposure throughout the world may be about one-fifth of the annual collective effective dose equivalent from natural sources of radiation. Although the individual doses received by workers involved with medical uses of radiation may be significant, the overall occupational contribution to the collective dose is insignificant compared with that from the irradiation of patients, because of the relatively small number of workers to be considered.

24. The Committee has previously presented data on medical irradiation in its reports issued in 1958, 1962, 1972 and 1977. However, in view of the limited information available and of the uncertainties attached to the dose estimates, trends in the collective dose over the years cannot be easily assessed. In industrialized countries an increasing number of examinations has taken place over the years; on the other hand, continuing improvement in the equipment that has occurred during this period should have resulted in a lower dose per examination. These two trends may have balanced out to some extent. For the purposes of the comparisons made in this report, the Committee has assumed a roughly constant annual collective dose from medical exposure.

(b) *Nuclear explosions*

25. Artificial radioactive material from nuclear weapons tests in the atmosphere was the cause of widespread contamination of the environment. Much of this material was initially injected into the upper atmosphere, from which it transferred slowly to the lower atmosphere and then to earth in a process usually referred to as fallout. The radionuclides occurring in fallout give rise to exposure by inhalation while they are present in ground level air, or by external irradiation and ingestion when they are deposited onto plants or in the soil.

26. Nuclear explosions have been conducted since 1945. Intensive nuclear test programmes in the atmosphere took place during 1954–1958 and 1961–1962. Since 1964, additional atmospheric explosions have occurred, the latest one in October 1980. Underground nuclear explosions have been, and still are being, conducted but the resulting environmental contamination is relatively minor. As in all its previous reports, the Committee has assessed the exposures to which the population of the world has been subjected as a result of the atmospheric nuclear tests. Although several hundred radionuclides are produced by nuclear explosions, only a few contribute significantly to human exposure, since most of them decay within a short time or are produced in very small amounts. The Committee, in this report, has considered 21 radionuclides, including iodine-131, strontium-90, caesium-137 and carbon-14. Because of the wide range of decay times, the doses resulting from a nuclear test are delivered at a varying rate after the explosion. For example, the doses from iodine-131 are delivered in a matter of weeks, those from strontium-90 and caesium-137 are completed in a few decades, while doses from carbon-14 will be delivered over thousands of years.

27. At any given time, the doses depend also on the location being considered. There is a latitudinal variation in fallout which has caused the doses in the southern hemisphere to be generally lower than in the northern hemisphere by a factor of about four. In addition, local fallout (in the vicinity of a test site) has occasionally given rise to higher individual doses for small groups of population.

28. The annual collective doses expressed as percentage of the average exposure to natural background provide an illustration of the yearly trend of the exposure from nuclear tests. The long-term trend, derived from data contained in this report and in the previous reports of the Committee, is illustrated in Figure I(a). There was a sharp increase of the annual collective doses in the early 1960s leading to a peak in 1963, corresponding to about 7% of the average exposure to natural sources. In 1966 the annual dose had decreased to approximately 2% of the annual average exposure to natural sources and it is at present less than 1%. Assuming no further atmospheric explosions, the future annual doses will become smaller and smaller until they vanish out completely.

29. The average annual collective doses received by the world population at any given time shown in Figure I(a) are the result of all the explosions that have taken place up to that time. It is also of interest to study the trend of the collective doses that were committed until complete decay of the radionuclides released by each year of testing. This is done in Figure I(b) which shows that explosions in the years 1961–1962 were the major

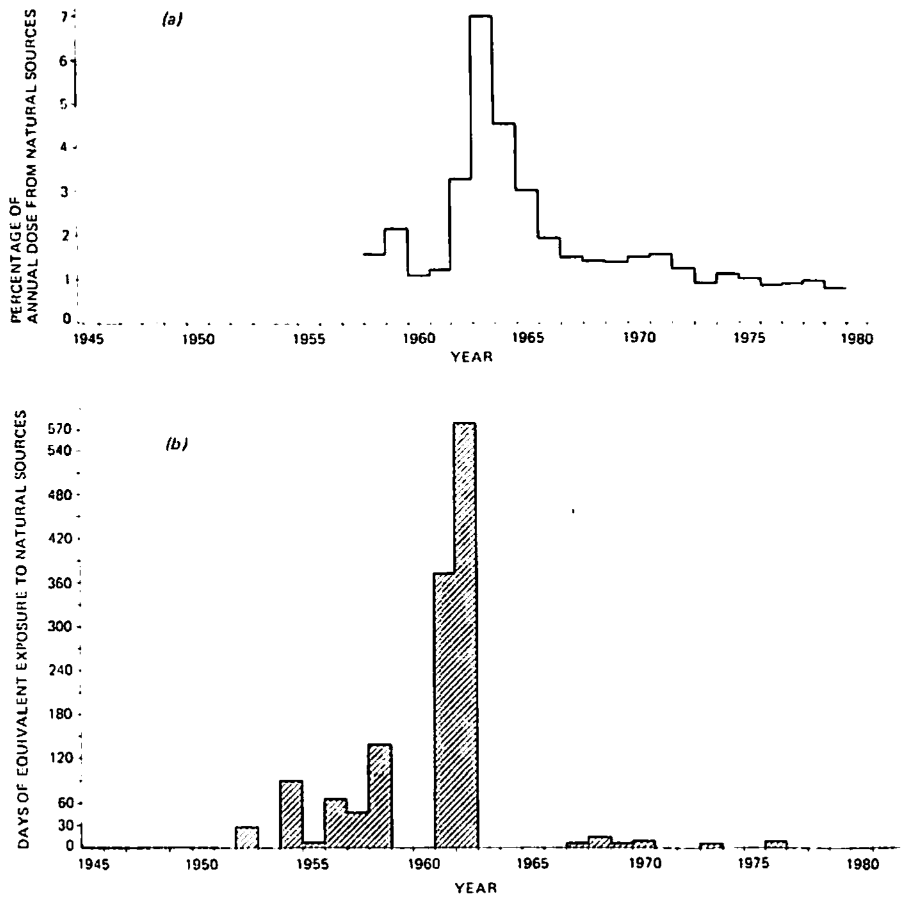

Figure I. Trends with time of collective doses from nuclear explosions in the atmosphere. (a) Average annual collective doses received in 1958–1979; (b) Collective doses committed for the future by explosions carried out between 1945 and 1980

contributors to the total impact of fallout from weapons testing carried out so far.

30. In Figure I(b) collective doses are expressed in terms of the number of days of exposure of the world population to natural radiation which would cause the same impact. If the doses received by the world's population could have been delivered at a constant rate equal to that of the average exposure to natural radiation sources, instead of at a low and irregular rate over more than thousands of years, then the total collective dose would equal that currently received from natural sources in about 4 years. It can thus be said that the impact from fallout corresponds to about 4 years of average natural background. The collective doses delivered so far can be derived from Figure I(a) and amount to about 0.4 year of exposure to natural sources. The rest, that is, about 3.3 years of natural background, corresponds to doses from fallout which will be delivered until complete decay of the radionuclides released. Fifty per cent of the impact from fallout will be delivered at a small rate in the next 2000 to 3000 years.

(c) *Nuclear power production*

31. The number of nuclear reactors in operation has increased since the previous report of the Committee to include, in 1979, 235 reactors with a total installed nuclear generating capacity of about 120 gigawatt (GW). The production of electrical energy by nuclear reactors presupposes the existence of a fuel cycle which involves many steps. They are: mining and milling of uranium ores; conversion to various chemical forms; enrichment of the isotopic content of uranium-235 (in some cases); fabrication of the fuel elements; production of power in nuclear reactors; reprocessing of irradiated fuel (in some cases); transportation of materials between the various installations and, finally, disposal of radioactive waste. For each major step of the nuclear fuel cycle the Committee has evaluated the doses to workers as well as the doses to members of the public.

32. With respect to the latter doses, it should be realized that at any given time a source such as a nuclear power plant will deliver doses to individuals which are strongly dependent on their distance from the source. Also, for any given location of an individual, the dose due to the releases from the plant will change with time, including the time after the practice is terminated, owing to the radionuclides that remain in the environment. It is therefore difficult to give a value of the individual doses that might be representative of that source, although the total impact may be assessed by adding all the individual doses in space and time and over all individuals in the present and in the future. Indications concerning the individual doses can, however, be expressed in different ways.

33. For example, one could choose to give a value referring to the individual (present or future) who has received (or will receive) the highest dose from the operation of a given source. However, the actual individual doses will range between zero and that highest value. Alternatively, one could give, for any given year, the annual dose averaged over all people in the world, in other words the per caput annual dose.

None of the above estimates will provide a complete representation of the real situation, although each of them might be of some interest for special purposes.

34. In spite of all the above conceptual difficulties, it is nevertheless interesting for the exposed individuals to have some estimate of individual doses. For example, the maximum individual doses may provide some indication of the upper bound of risk that might be incurred on account of a given source. In an analysis of trends in time the average annual dose over the population of the world at a given time may give useful guidance. However, it should be stressed again that such values are indicative averages and may not be taken to refer to the actual exposure of any given individual.

35. Almost all the radioactive material associated with the nuclear industry remains in the reactor sites or in special storage facilities; but, at most steps of the operations, environmental releases of small quantities of radioactive material occur. Most of the radionuclides released are of local relevance only, because they decay rapidly. However some radionuclides, which have a longer life or are more rapidly dispersed, become globally distributed and contribute to the exposure of the entire population of the world, now and, in some cases, well into the future.

36. By rough approximations, the short-term annual collective effective dose equivalents to members of the public from these sources can be calculated to have increased from 0.0001% of the corresponding values from natural sources in 1960 to about 0.01% in 1980. The increase in dose is directly related to the expansion of nuclear power production in the same time. The annual doses to individual members of the public vary widely around the average value, the highest doses usually being received by population groups living in the vicinity of nuclear installations. Typical values around nuclear reactors are reported between a fraction of one percent to a few percent of the average annual effective dose equivalent from natural sources. In addition, radiation workers involved in the nuclear power industry receive annual effective dose equivalents which are typically of the order of the corresponding average value from natural sources.

37. The long-term component of radiation impact arises from releases of long-lived radionuclides during the operation of the plant and from effluents from mill tailings or from high-level waste disposal. The long-term component corresponding to a period of 500 years following the release has been crudely assessed. For one year of nuclear power production at the 1980 level, the impact of this long-term component on members of the public may represent about 2 hours of exposure to natural background, whereas the radiation impact of the short-term component is estimated to amount to about 30 minutes of exposure to natural radiation sources. Most of the effective dose equivalent from the long-term component stems from releases from mill tailings which may emanate radon over extremely long periods of time. The rate of emanation can be modified by improvements in management practices, which could result in decreases by orders of magnitude. In the far future (thousands to millions of years) the releases from mill tailings or from waste repositories will be influenced by geological and climatological changes, which are very difficult to predict. The dose estimates from those releases also depend on living habits in the far future, which might be very different from present ones.

38. On the assumption that the production of nuclear power by fission reactors may continue for 500 years at the present rate, the Committee estimates that the maximum annual collective effective dose equivalent may amount to a fraction of one percent of the corresponding dose received annually from natural sources of radiation. It must be emphasized that this long-term forecast is based on existing technologies and is therefore subject to change. It is likely that changes in present technologies such as the introduction of fast reactors or other advanced fuel cycle technology, or the containment of long-lived radionuclides may further reduce the long-term impact of future practices.

39. The contribution of occupational exposures to the impact from nuclear power production is much easier to assess as most radiation workers are individually monitored. At the present level of nuclear power production, the annual collective effective dose equivalent resulting from occupational exposure amounts to about 0.03% of the corresponding value from natural radiation sources.

B. NEW DEVELOPMENTS IN RADIOBIOLOGY

40. Radiation induces biological effects essentially through the deposition of energy in the cells of the irradiated individual. Two classes of cells may be visualized in this respect: the somatic cells, which do not survive beyond the life span of the individual; and the germinal cells, whose function is to transmit genetic information to new individuals. The somatic effects of irradiation take place in the somatic cells and they must become apparent, by definition, within the life of the irradiated person. On the other hand, hereditary effects occurring in the second class of cells become apparent in the descendants of the irradiated persons within the first, or in some later, generation.

41. In general terms, the radiobiologically important effects interfere with the division of somatic cells in one of two possible ways: they may either cause the irradiated cell to stop dividing and eventually to die; or they may confer upon the cell a capacity for unrestrained division which is characteristic of cancer. A distinction is usually made between early and late effects of irradiation, according to the time at which such effects become manifest: a few hours to a few weeks in the first case; many months to many years in the latter.

42. It has been past policy of the Committee not to attempt to cover all biological effects in animals and man in any one report, but rather to review selected areas, depending on the amount of information accumulating and on the need to survey all fields at some interval of time. This report was compiled in the light of the same general policy. Among somatic effects, some non-cancerous consequences of irradiation administered to the whole body or to selected tissues are considered. Information on genetic effects is updated and assessed for the purpose of risk estimation.

1. Genetic effects

43. In the field of genetic effects, important conclusions were reached on the basis of recent publications. These have increased the Committee's confidence that

earlier assumptions and risk estimates remain essentially valid. These estimates have been compared with spontaneously-arising hereditary defects which affect, with different grades of severity, roughly 10% of all liveborn children. Physical agents such as ionizing radiation, as well as some noxious chemicals, may interact with the genetic material of the germinal cells in the testes or in the ovary by altering the genes, the elementary units of heredity (thus causing gene mutations), or with the structure or number of chromosomes on which the genes are carried (thus causing chromosomal aberrations). Changes in the genetic material may be associated with a variety of hereditary defects, some of which have severe clinical consequences.

44. Using gene mutations and chromosomal aberrations as end-points of experimental observations, data on dose-effect relationships have been compared in a variety of organisms. These comparisons have strengthened the assumption that one may expect a proportionality between the rates of spontaneous and of induced mutations of particular genes. This basic assumption has been applied in the indirect method of risk estimation.

45. Using the indirect method, the Committee estimated in 1977 that when a population is continuously exposed to low doses of low-LET radiation at a rate of 0.01 Gy per generation (1 generation = 30 years), 63 new cases of hereditary diseases per million first generation progeny would be expected. A substantial part of the hereditary diseases included in this estimate is related to those arising from numerical anomalies of chromosomes. However, data on experimental animals and man point to the possibility that the estimate for diseases falling under the category of chromosomal diseases may be lower than previously estimated. In view of this, the Committee has now estimated that when a population is exposed under the conditions specified above, the increment in genetic diseases is likely to be of the order of 20 (instead of 63) cases per million births in the first generation and about 150 (instead of 185) cases per million births at equilibrium (or about 2000 and 15 000 cases in the first generation and at equilibrium, respectively, when the exposure is at a rate of 1 Gy per generation).

46. As in the 1977 report, an estimate of risk for hereditary disorders has also been made using the direct method. The estimated values using these two different methods (i.e., indirect and direct methods) are in reasonable agreement.

47. The risk from the induction of a particular type of chromosomal effect of radiation (reciprocal translocations) has been re-evaluated on the basis of results from studies in marmosets, rhesus monkeys and man. However, the health consequences to the individuals carrying such translocations cannot be reliably assessed at present.

48. Further advances have been made in our knowledge of the dose-response relationships and other aspects of some of the more important types of genetic changes which can be induced by radiation in experimental mammals. Extensive use of experimental data for genetic risk assessment is still considered essential in the absence of significant results with respect to hereditary effects after human exposures. Suggestions have also been formulated for more detailed analyses of genetic effects with respect to detriment.

2. Somatic effects

49. One of the conclusions of the present report is that at low doses and dose rates the induction of non-neoplastic effects is not observed. This conclusion holds true for both whole-body and specific organ irradiation. At comparable doses and dose rates cancer induction may be the only somatic consequence of irradiation in animals and man.

50. In its 1977 report the Committee discussed factors which make any accurate assessment of risk of cancer induction in man very difficult. In spite of such difficulties, the Committee provided at that time an analysis of the human data and of the risk estimates to be derived therefrom, to be used as a necessary starting point for decisions of practical value, particularly as scientific criteria for radiation protection policies.

51. In view of the limited amount of new epidemiological evidence, there would have been no merit in repeating the same analysis in a short time interval. The Committee undertook instead to review whatever information might be of interest, in experimental animals and in man, in the light of some basic models of tumour induction. The scope was to assess the possible errors that might affect the estimates if one or another model of radiation action applied. Such a study might be regarded as an indirect way of estimating risk ranges at the low doses and dose rates where direct evidence is not available.

52. The Committee decided, however, to postpone the publication of a document based on this study when it became known that revisions had been proposed to the dosimetric estimates for the survivors of the atomic bombs at Hiroshima and Nagasaki on which some of the Committee's analyses had been based. Not only the total doses received by the exposed populations, but also the relative contributions of the neutron and gamma-ray components in the presently used T65D (Tentative 1965 Dose) were called into question. The effect of the proposed revisions is to reduce the neutron dose component at both cities and to increase the gamma component at Hiroshima substantially, while reducing the gamma component at Nagasaki slightly. In addition, many more factors must be examined and taken into account before reliable revised estimates of individual organ doses can be determined for the survivors. This matter is technically complex, and it appears unlikely that the proposed revisions can be thoroughly investigated and agreed upon within a short time.

53. The Committee awaits with interest the results of further studies in this field, as they would form one of the bases on which radiation risk estimates in man must be founded. In the meantime the Committee wishes to emphasize that it does not expect a significant impact of these revisions on the risk estimates contained in the 1977 report of the Committee, namely, that the risk of fatal cancer induction for x and gamma rays is of the order of $2\ 10^{-5}$ for an effective dose equivalent corresponding to one year of natural background, as an average for both sexes and all ages. This is so for two reasons. First, while it is impossible yet to say exactly what influence the revisions, if accepted, will have on the risk estimates, it is unlikely that this influence will exceed a factor of 2. Indeed, improved agreement between data from Hiroshima and Nagasaki may tend ultimately to strengthen confidence in the estimates. Secondly, the information derived from the survivors of

the atomic bombs in the two cities is only one of the sources of human exposure that the Committee has used in arriving at its estimates.

54. While little change is therefore expected to result in regard to estimates for cancer induction in man by x and gamma rays, an important presumed source of information for whole-body neutron irradiation will no longer be available if these dose revisions are indeed substantiated. The calculation of the doses to the atomic bomb survivors of Hiroshima and Nagasaki will be kept under close scrutiny and the Committee will continue to study dose-effect relationships.

55. A large amount of information has been available on the effects in man of irradiating selected organs and tissues for radiotherapy of various types of disease, mostly cancer. There was a need to review these data and to verify their consistency with information obtained for different purposes in experimental animals. The Committee's study considered: the nature of the early and late non-stochastic damage (see Annex J) induced by radiation on normal tissues; the dose thresholds at which specific forms of early damage may become apparent in various animal species, and particularly in man; the effect of some important variables of exposure (radiation quality, fractionation of treatment) on these thresholds.

56. Two unifying concepts emerged. First, tissue damage depends primarily on the loss of reproductive capacity of some of the constituent cells; second, the structure and function of each tissue determines to a large extent the time and magnitude of its observed response. It was necessary to derive, from experience collected mostly at high doses and dose rates, information applicable at low doses and dose rates, which are the irradiation conditions of most interest in practice. Finally, it was necessary to rely on experience derived from exposure of normal human tissues during radiotherapy.

57. The study was useful for the great amount of information it provided in respect to each particular tissue. The most general conclusions to be drawn from such a complex analysis are that non-stochastic tissue effects are generally characterized by non-linear relationships with dose and apparent thresholds at low doses. These conditions are of paramount importance for any consideration of non-stochastic tissue damage. Although the magnitude of the threshold may vary for each tissue and for each specific effect, the mechanisms producing the effects make it unlikely that thresholds will be abolished at low doses and dose rates. Thus, if a non-threshold response applies or is assumed to apply for induction of cancer, it follows that this latter might be induced at the low doses where the threshold would prevent expression of the non-stochastic damage to be seen. In this respect the induction of cancer may in general be regarded as the most important effect at low doses and dose rates for planning of radiation protection.

58. In cases of partial-body irradiation it is, in principle, easier to attribute the resulting damage to target cells in organs and tissues than in the case of whole-body irradiation, where effects and symptoms may be of doubtful significance and of uncertain pathogenesis. A typical example is to be found in an effect of whole-body irradiation which is commonly, and incorrectly, referred to as "aging" or "non-specific life span shortening". The Committee has carried out an analysis of the experimental findings regarding radiation-induced aging in animals and man. Since the biological mechanisms of natural aging are essentially unknown, there appears to be insufficient ground to postulate a possible effect of irradiation in the absence of convincing experimental data; this possibility may not, however, definitely be ruled out. The study was therefore limited to the radiation-induced shortening of life.

59. Although the length of the life span is usually taken as a measure of aging, it represents simply the actuarial aspect of it, and ignores the complex interplay of factors leading to death. It is well known that, on the average, the life span of irradiated animal and human populations tends to be shorter than the life span of suitably matched controls. However, to ascertain the causes of death may be an exceedingly difficult task, though the only reasonable means to attribute death to specific causes and thus to decide on the reality of possible non-specific mechanisms. An overwhelming body of literature shows that at low doses and dose rates life shortening is essentially caused by the occurrence of cancers at above the spontaneous rate. When the contribution to life shortening by these cancers is subtracted from the total life shortening effect, there is no evidence of other non-specific mechanisms being responsible for additional shortening. This conclusion is well documented and it applies in humans and in other mammals. There is indeed some conflicting evidence but this does not, in the Committee's opinion, carry sufficient weight to invalidate the conclusion. Further study on this point may be required.

60. It is essential that risk estimates be formulated with a wide perspective of possible applications. In this connection it is important to ascertain if the effects of ionizing radiation, a ubiquitous agent in nature, could be modified by the interaction with other agents (physical, chemical or biological) having a widespread distribution in the environment and therefore apt to affect large numbers of people and, possibly, to cause changes of the risk estimates.

61. Although the possibility of such interactions has often been suggested, the amount of positive information, particularly regarding effects that are significant for risk estimates in humans (induction of cancer, hereditary effects, developmental abnormalities), is rather scanty and inconsistent. The analysis of the Committee was therefore of necessity mostly theoretical, with illustrations drawn from published work. It has, however, demonstrated the complexities of a thorough scientific treatment of this matter because the nature of the interacting agents, the variable mechanisms of action, the doses, the order and the schedules of administration allow a variety of possible interactions.

62. The study reviewed some agents which are important under specific conditions, mostly occupational, among which the best documented is the interaction of tobacco smoke and alpha-irradiation by radon daughters for lung tumour induction in uranium miners. Although this finding is certainly applicable to specific occupational situations (and may be relevant to actions by local authorities) the review of the Committee indicates that it does not decrease the general validity of the broad use of radiation risk estimates. There is a need for more research to be directed towards these problems, with coherent strategies and sensible choices of the agents to be investigated. The Committee has made recommendations in this respect.

III. MAIN TEXT OF THE REPORT

63. After an initial section outlining the concepts and quantities used by the Committee in its assessments, this chapter systematically covers, for the various fields of interest, specific conclusions to be drawn from the Committee's studies since the presentation of the last substantive report. Each section is preceded by a paragraph which summarizes the content of the section. The data and the analyses on which the Committee's conclusions are founded are given in the scientific Annexes A to L.

A. QUANTITIES AND UNITS

64. In studies of radiation effects it is customary to correlate the probability of the response or the magnitude of the effects with estimates of the exposure to radiation. The primary quantity used for this purpose is the energy absorbed per unit mass of the irradiated biological object, which is called the absorbed dose.

65. For risk assessment it may be desirable to weight the contribution of different radiations in order to account for their different biological effectiveness. One weighted quantity defined by ICRP for the purposes of radiation protection is the dose equivalent, which is derived by weighting the dose of a given radiation with the quality factor based upon a range of experimental observations. The dose equivalent, H, is thus the product of the absorbed dose, D, and of the quality factor, Q, together with any other relevant factor recommended by the ICRP.

66. An important development for the purpose of risk assessment that has taken place recently and is used in this report is the definition of effective dose equivalent. This stems from the need for both uniform and partial irradiations of the body to be taken into account for risk evaluations. To this end it is necessary that the weight to be assigned to irradiation of a given part of the body should be in proportion to the risk of developing stochastic effects, by comparison with effects expected from whole-body irradiation with the same dose equivalent. For example, if, for the same dose equivalent, irradiation of an organ results in 10 times less effects than would be expected to result from irradiation of the whole body, it would be necessary, in order to maintain equality of the risk when summing exposures of different organs, to assign 10 times less weight to the organ than to the whole-body dose equivalent. A list of weighting factors applying to various organs has been provided by the ICRP for the purposes of radiation protection and these same factors have been used throughout this report.

67. The effective dose equivalent, as defined by ICRP, was not designed for risk estimates, but was introduced as a suitable dosimetric quantity for comparison with administrative dose limits. Since the organ weighting factors are average values for all ages and both sexes, the effective dose equivalent is not well suited to reflect the probability of radiation-induced cancer and severe hereditary harm from exposures of single individuals but will indicate the average risk for a heterogeneous population of both sexes and all ages.

68. For such populations, the expectation of harm from low doses of radiation is postulated to be proportional to the collective dose, which is the average individual dose multiplied by the number of individuals exposed. The radiological impact of a given source of radiation can therefore be assessed by summing individual contributions to the collective dose over space and time. When related to the particular practice that is assumed to cause these present and future exposures, this sum is called the collective dose commitment from that practice.

69. In conclusion, weighting of absorbed doses to derive dose equivalents makes allowance for the biological efficiency of different types of radiation. Use of the effective dose equivalent takes into account the relative risk of exposures of different organs of the body. The collective dose permits an estimate of the expectation of harm in an exposed population. The commitment concept relates the total future expectation of harm to the practice that causes the exposure. In spite of their apparent complexity, these concepts facilitate assessments and intercomparisons of doses and risks from different sources of radiation.

70. In considering the radiation spontaneously emitted from a radioactive material it is convenient to characterize such emissions in terms of activity (of the radionuclide). Activity is the number of nuclear transitions of the radionuclide per unit time. The SI unit is reciprocal second (s^{-1}). The special name for reciprocal second, when used for activity of radionuclides, is becquerel (Bq). Thus

$$1\ s^{-1} \equiv 1\ \text{Bq (for activity)}$$

The SI unit for both absorbed dose and dose equivalent is joule per kilogramme (J kg^{-1}). The special name for J kg^{-1}, when used for absorbed dose, is gray (Gy). Thus

$$1\ J\ kg^{-1} \equiv 1\ \text{Gy (for absorbed dose)}$$

The special name for J kg^{-1}, when used for dose equivalent, is sievert (Sv). Thus

$$1\ J\ kg^{-1} \equiv 1\ \text{Sv (for dose equivalent).}$$

B. RADIATION LEVELS AND DOSES

1. Dose assessment models[4]

71. To calculate the dose delivered by radiation sources to exposed populations it is necessary to use models linking the measured or calculated amounts of radioactive materials that are released by the source or that are present in the environment, with the resulting dose in the exposed subjects. Environmental transport models and dosimetric models are used for this purpose. As background information for the assessments which follow, this section provides a description of the main models used by the Committee.

[4] This subject is reviewed extensively in Annex A "Dose assessment models".

72. The Committee reviews the information on human radiation exposure for several purposes. One purpose is to assess the levels of exposure to which individuals are subjected, another is to assess the levels of exposure to population groups, a third is to provide basic data. The relationship between the level of exposure of an individual and the probability of induction of health effects which are presumed to result is extremely complex. At the present state of knowledge it is reasonable to assume that an increased exposure carries with it an increased risk of harmful effects. The principal assumption underlying, implicitly or explicitly, the Committee's evaluations is that the probability of occurrence of stochastic effects in a given tissue is linearly proportional to the dose equivalent in that tissue, down to the lowest doses and with a proportionality factor which is different for various tissues. The importance of this basic model cannot be overemphasized because, in the absence of linearity, it is not permissible to add doses to give a measure of the total risk, nor to calculate collective doses as expressions of the total detriment to exposed populations.

73. When individuals at work are being considered, it is usually possible to evaluate the level of exposure from direct measurement. The doses resulting from such exposures over a given period of time (e.g., one year, the working life, the whole life time) provide an indication of the presumed level of risk incurred. When assessing exposures to members of the public, considered either individually or collectively, the level of exposure cannot be measured directly and must be assessed by indirect means. This is accomplished by the use of models linking the measured or calculated amounts of activity that are released by a source or that are present in the environment, with the resulting doses in the exposed individuals. Models of this sort fall into two broad categories: environmental and dosimetric. Environmental models describe the movement of radionuclides from the point of release through various sectors of the environment. Dosimetric models include those for predicting the behaviour of radionuclides inside the human body after their intake and those for providing estimates of the resulting doses to organs from radionuclides in the body or from external sources.

74. If it is possible to measure the absorbed dose rate in air from radionuclides in the air or deposited on the ground at a sufficient number of places and over a sufficient time, then the absorbed doses to individuals and populations from external irradiation can be assessed without the need for environmental transfer models to describe the manner in which the airborne contamination or deposition resulted from the source of radionuclides. Similarly, if the activity concentrations in organs or tissues of the radionuclides concerned can be measured in a sufficient number of people, the absorbed doses from incorporated radionuclides can be assessed using only dosimetric models and without the need for environmental transfer models. In many situations, especially for naturally-occurring radionuclides and for those produced from nuclear explosions, sufficient measurements have been carried out in different places and over long enough periods of time to enable the Committee to estimate doses directly from them.

75. Slightly less direct estimates of internal doses can be made from measurements of activity concentrations of radionuclides in the air or in foodstuffs. In this case the additional information required is the intake rates of the radionuclides from air or from the foodstuff concerned, and the appropriate dosimetric models to provide the absorbed doses in organs and tissues following intake. These less direct methods are used for some radionuclides from nuclear explosions, often to supplement a more limited measurement programme on people. They are also used in assessing absorbed doses to critical groups of the population exposed as a result of deliberate releases of radionuclides from nuclear installations, for a limited number of radionuclides. A difficulty in placing too much reliance on such measurements is that there has to be a great deal of preliminary effort to ensure that the foodstuff being monitored is the only, or the major, route of intake of the radionuclide concerned. When dealing with a mixed diet and a large number of radionuclides this becomes extremely laborious. For radionuclides which are not evenly distributed in the environment it is not a feasible method to establish the collective dose.

76. Sometimes direct measurements may not be practicable. This may be due to technical difficulties in measuring the activity concentration of the radionuclide concerned in an appropriate medium, or to the difficulty of obtaining samples, or to the number of radionuclides and pathways being too large. Direct measurements may also be impracticable because predictions of dose rates are required, for example to derive collective dose commitments, rather than measurements which have to be carried out after or during the delivery of the dose. In these cases models are necessary in order to derive doses and dose distributions from data on the quantities of radionuclides released into the environment and the rates of release. The relationship between doses and releases will depend on many factors, such as the conditions of the release, the physico-chemical form of the radionuclide, whether the release is into the atmosphere, a water body or the ground, and the characteristics of the receiving environment. In general, the environmental models with which the Committee is concerned are simplified mathematical representations of actual transfer processes. Some of those processes are well understood and can be described reasonably precisely by mathematical models which are very closely based on measurements. The transfer of fallout radionuclides such as strontium-90 through food chains is an example. Other processes may only be partially known and the time scales or other aspects may render it very difficult to verify the models by measurement, as in the case of the long-term stability of sorption of actinides on soils or sediment particles.

77. Annex A reviews the models used by the Committee but a detailed account of all these is beyond the purpose of this chapter. Suffice it to say that the Committee describes, in that Annex, the atmospheric (local, regional and global), the aquatic (rivers, lakes, oceans) and the terrestrial transport models used throughout all other Annexes. It also reviews the bases of the models and the detailed pathways for various modes of irradiation. This material is regarded as necessary background information for the dose assessments in all cases involving environmental dispersion of radioactive substances.

2. Exposure to natural radiation, including the technologically modified sources, and to radiation-emitting consumer products

78. The main conclusion to be drawn from the work of the Committee in this area is that the dominant contri-

bution to the collective dose from natural sources may be attributed to the decay products of a noble gas, radon. New studies have investigated a number of radon sources such as building materials, radon released from ground, from tap water and from natural gas. A number of parameters are also being studied (emanating power, building technology and, particularly, ventilation) which may greatly influence the contribution of this source. The realization of the importance of these factors coincides with technological developments which increase the radon concentration indoors. Exposures to other natural sources, to enhanced natural radiation or to various consumer products, have not been found to depart substantially from previous assessments.

79. The Committee has reported frequently on natural sources of human exposure because they are at present (and are likely to represent also in the foreseeable future) the largest part of the collective dose received by the population of the world. Their ubiquitous nature and the very low and fairly constant rate of delivery during the whole of man's life time are the main characteristics of these sources. Improvements in knowledge of natural exposure, with the exception of the exposure to the decay products of radon, have not been very substantial since the 1977 report. The present treatment is therefore essentially an updating. However, some new information on technologically modified exposures to natural radiation and to consumer products has resulted in a better assessment of the sources and of the doses therefrom.

80. Any form of life on earth is unavoidably associated with exposure to radiation from natural sources. These may be of two different kinds: sources in the extraterrestrial environment (i.e., cosmic rays) and terrestrial sources (i.e., the radioactive substances in the earth's crust). These irradiate the human body from outside. There arises also, however, from both types of sources, internal exposure from naturally occurring nuclides which are taken up into the body through normal physiological pathways. When living in a natural environment man is exposed to all these sources.

81. There are circumstances, related mostly to technological developments, in which human exposure to these natural sources can be modified. Air travel, the use of natural gas for heating purposes, and living in the vicinity of power plants burning fossil fuel, are examples of conditions giving rise to enhanced exposure to natural radiation. These exposures would not occur if the related technologies (not expressly designed to produce radiation) had not been available. In this report these exposures are referred to as "technologically modified natural exposures" and are treated separately from the truly natural ones.

82. Since it is known from previous analyses of the Committee that a substantial part of the dose received by internal exposure is due to inhaled radon, thoron and their decay products, a comprehensive study of these radionuclides was undertaken for the present report. The study relates to the levels of these nuclides in the living and working environments, to the extent and causes of their variability in nature, and to the conditions affecting the dose delivered by these nuclides in the course of human exposure, particularly of the lung. The results of this study will be discussed separately (see paragraphs 108–116).

83. Finally, there are exposures to widely used consumer products, arising either because radioactive materials are deliberately incorporated in them, or because radiation is produced in the course of their normal function. Exposure to consumer products is similar in a way to exposure to technologically modified sources; their joint treatment with the technologically modified sources is, however, essentially a matter of convenience.

(a) *Natural sources*[5]

84. With regard to external exposure, the Committee has evaluated the doses from cosmic rays (both the ionizing and neutron components) separately from the doses due to terrestrial irradiation produced by potassium-40, uranium-238, thorium-232 and their decay products. The cosmic ray component is usually very stable at the earth's surface, but it does vary with the geomagnetic latitude and, to a greater extent, it increases with the altitude above sea level. Thus, population groups living at high altitudes receive substantially higher doses than others living on low land or at sea level. The external dose equivalent received from cosmic rays by populations living at sea level is about 0.3 millisievert per year.

85. The terrestrial component of the natural background is dependent on the composition of the soils and rocks in which natural radionuclides are contained. There is sufficient information concerning the outdoor terrestrial radiation doses over large areas of the world to state that the majority of the population residing in these areas receives of the order of 0.35 millisievert per year, with a standard deviation of the order of 25% of this average value. This figure is derived from knowledge that exposure rates indoors are on the average about 20% higher than outdoors and from the assumption that people spend 80% of their time indoors. This population weighted average may reasonably be thought to represent the "normal" level of terrestrial radiation to which mankind is exposed. Based on averages applying to large numbers of adult subjects living in areas of normal background, the external dose received from terrestrial irradiation is slightly higher than that from cosmic rays.

86. There are regions of the world where external exposure from natural terrestrial sources may substantially exceed the normal variability ranges. Such areas have been identified (and in some cases rather carefully mapped) in Brazil, India, Iran, Italy and other countries. In some of these locations the yearly dose received by the inhabitants may be more than 10 times greater than that received by people living in areas of normal background. The relevance of these high background areas to the global collective dose from external exposure has not yet been ascertained with great accuracy. Current estimates are that this contribution does not exceed 10% of the global collective dose.

87. Internal exposure resulting from radionuclides entering the body through ingestion or inhalation has also been assessed by the Committee. These radionuclides are either cosmogenic (i.e., produced by the interaction of cosmic rays with atoms in the upper atmosphere) or primordial, in the sense that they have existed in the earth's crust throughout its history. Very little of the dose from natural background is contributed by the first class of nuclides. Tritium (hydrogen-3), beryllium-7, carbon-14 and sodium-22 are the only

[5] This subject is reviewed extensively in Annex B "Exposures to natural radiation sources".

components adding significantly to the dose. Of the latter class, the short-lived decay products of radon-222 are by far the most important contributors. Then follow potassium-40, the decay products of thoron (radon-220) and polonium-210. The effective dose equivalent from internal sources of natural radiation may be estimated to be about two times that from external exposure. However, groups of people living under special housing conditions may be exposed to considerably elevated internal absorbed doses.

88. Table 1 summarizes data relating to various sources of natural exposure in terms of effective dose equivalent. The per caput global annual effective dose equivalent resulting from natural sources of radiation is estimated to be 2 millisievert, about half of which is due to indoor inhalation of the short-lived decay products of radon-222 and radon-220 which are part of the uranium-238 series and of the thorium-232 series, respectively. The relative importance of the contribution from the short-lived decay products of radon-222 and radon-220 stems from the use of the new concept of effective dose equivalent. This implies the multiplication of the absorbed dose in lung by a quality factor of 20 for alpha particles to calculate the dose equivalent in lung, and a multiplication by a factor of 0.12 which is the organ weighting factor for the lung in the derivation of the effective dose equivalent. The overall conversion coefficient from absorbed dose in lung to effective dose equivalent is thus 2.4 sievert per gray. As the corresponding overall conversion coefficients for the other significant contributors to the exposures from natural sources are equal to one or less than one sievert per gray, the effective dose equivalent from the decay products of radon-222 and radon-220 is given a higher prominence. The average indoor concentrations of radon-222 and radon-220 are expected to vary from one region of the world to another according to the rate of ventilation and to the type of dwelling. It is estimated in this report that, by comparison with the average global value, the exposure from the decay products of radon-222 and radon-220 are about 25 per cent higher in the temperate latitudes and about 70 per cent lower in the tropical latitudes, resulting in average annual effective dose equivalents from natural radiation sources of 2.2 and 1.3 millisievert in temperate and tropical latitudes, respectively. The global average value of 2 millisievert in a year is reasonably consistent with the estimates presented in the 1977 Committee's report in terms of absorbed dose. The annual global collective effective dose equivalent is thought at present to be about 10^7 man sievert.

TABLE 1. ESTIMATED ANNUAL EFFECTIVE DOSE EQUIVALENTS FROM NATURAL SOURCES OF RADIATION IN AREAS OF "NORMAL" BACKGROUND

	Annual effective dose equivalent (millisievert)		
Source	*External irradiation*	*Internal irradiation*	*Total*
Cosmic rays			
Ionizing component	0.28		0.28
Neutron component	0.02		0.02
Cosmogenic nuclides		0.015	0.015
Primordial nuclides			
Potassium-40	0.12	0.18	0.30
Rubidium-87		0.006	0.006
Uranium-238 series	0.09	0.95	1.04
Thorium-232 series	0.14	0.19	0.33
TOTAL (rounded)	0.65	1.34	2.0

(b) Technologically modified natural sources[6]

89. The following subsection summarizes the characteristics of sources previously defined as "technologically modified" (see paragraphs 81–83).

90. *Coal fired power plants.* Coal contains trace levels of natural radionuclides and its combustion results in their release to the environment. Their redistribution from deep in the earth crust to the environment may significantly modify ambient radiation fields and population exposure. New information has become available on activity measurements in coal and on the behaviour of the radionuclides in and around power plants. Some estimate of doses arising from this source of exposure may now, therefore, be carried out.

91. When coal is burned, the mineral matter is fused into vitrified ash. Most of this is retained in the power plant as slag-ash but the lighter portion, the fly-ash, is carried with the hot gases to the stack of the plant from where, depending on the efficiency of the collecting devices, some fraction is released into the atmosphere. An estimate of the average releases of radionuclides in the atmosphere has been obtained from reported discharges and measured concentrations in coal and ash. The estimated discharges are thought to be representative of the current situation world-wide.

92. The main pathways of exposure of the population living around the power plants to the radionuclides emitted are considered to be the following: inhalation during the passage of the plume, external exposure, and inhalation and ingestion resulting from the radionuclides deposited on the ground. Doses to the various parts of the body may reasonably be calculated and dose commitments estimated for the various nuclides.

93. In terms of the collective effective dose equivalent commitments, each of the three pathways mentioned is found to contribute significantly. The predominant components are the isotopes of thorium (for inhalation during the passage of the cloud) and the isotopes of radon (for internal exposure resulting from the activity deposited). Assuming that 70% of the coal mined throughout the world is used for power production and that one gigawatt year of energy produced requires the burning of 3 million tonnes of coal, the collective effective dose equivalent commitment resulting from the use of coal in 1979 is calculated, world-wide, to be about 2000 man sievert. The combustion of coal for other uses will add a somewhat larger amount.

94. *Use of phosphate rock.* Phosphate rock is extensively used as a source of phosphorus for fertilizers. It contains trace amounts of uranium-238, radium-226, thorium-232 and potassium-40, which are redistributed to the environment in the course of the rock's industrial processing and use. This comes about through effluent discharges, the agricultural use of fertilizers, and the utilization of by-products and waste material for other purposes.

95. Industrial effluents give rise to variable concentrations of the relevant radionuclides in airborne or liquid discharges. The type and amount of radionuclides released depend very strongly on the technology used for the rock processing. Inhalation during passage of the cloud, and the uptake of activity deposited onto

[6] This subject is reviewed extensively in Annex C "Technologically modified exposures to natural radiation".

soil, are the main mechanisms of irradiation; for each of them very approximate dose assessments can be provided and are discussed in Annex C.

96. Dose assessments are also possible for the radionuclides contained in the fertilizers. From knowledge of the world production of fertilizers, of the radionuclide content of these substances, of their distribution and use, of the radionuclide levels in the treated food crops, etc., approximate estimates of dose may be obtained. These doses are delivered to people occupationally exposed to the fertilizers, and to members of the public by various mechanisms of external or internal exposure.

97. The main by-product of the processing of phosphate rock is phosphogypsum in wet-process plants. In thermal-process plants calcium silicate slag is the main end-product. Phosphogypsum is used instead of natural gypsum in prefabricated building elements, calcium silicate in railroad and concrete constructions. Both these materials may contain much higher concentrations of radium-226 than most natural products. Radiation exposure of members of the public results from the above-mentioned uses and in view of the nuclide composition and of the conditions of irradiation, exposure would be expected to be significant, e.g., up to 30% higher, for persons living in houses built using phosphogypsum.

98. The Committee assessed the radiation exposures that might result from the full cycle of exploitation of phosphate rock, using reasonable simplifying assumptions and considering the most important radionuclides. Under the assumption that 10% of the phosphogypsum produced may be used in houses, the Committee came to the conclusion that by far the most important contribution to the collective dose resulting from the exploitation of phosphate rock would be derived from that source. If that use could be avoided, the rest of the dose commitment would only amount to about two thousandths of the potential dose.

99. *Use of special building materials.* Other materials have been found to deliver high doses to the inhabitants of dwellings built with them. They include: pumice stone, alum-shale concrete, lithoid tuff, granite, and tailings from uranium mills. The doses are due to high concentrations of potassium-40, radium-226 and thorium-232. In some countries, sampling of many building materials revealed, in certain cases, excessive concentrations of the above nuclides. However, the average absorbed dose rates measured in buildings containing such materials is often much lower than might be expected from the radioactive content of the materials considered, because usually less active materials are also used in the same buildings.

100. *Enhanced exposure to cosmic radiation.* During flight, passengers are exposed to higher dose rates from the cosmic component, which increases appreciably as a function of altitude. For example, an increase by a factor of 20 in the dose rate is observed between the altitudes of 4 and 12 kilometres. It has been estimated that the collective effective dose equivalent to the world population due to commercial flight in 1978 amounted to about 2000 man sievert. Similar evaluations have been performed specifically for the case of supersonic air transport. In spite of the fact that, due to altitude, radiation of solar origin does add to the galactic component and that during occasional intense solar flare radiation levels may increase substantially, these sources of exposure do not at present contribute significantly to the natural radiation exposure of the world population. Individual doses received by persons such as airline crew members are not however negligible.

101. The examples of technologically modified exposures brought to the attention of the Committee are likely to be incomplete. From the assessments performed, the Committee concludes that these exposures do not add significantly to the collective dose received by mankind on a world scale. However, in localized areas or for population groups exposed under extreme conditions, appreciable increases in individual doses from natural radiation may occur. The present state of knowledge does not allow very accurate estimates of the collective doses incurred from these sources. Further research is required to this end.

(c) *Radiation-emitting consumer products*[7]

102. *Luminous timepieces.* The energy emitted during the radioactive decay of radium-226, promethium-147 and tritium may be converted into light by a scintillator. This phenomenon has been used extensively in the dial painting industry for the illumination of timepieces and other scientific devices. Recently tritium has been used instead of radium, because its radiation is less penetrating than that accompanying the decay of radium and of its daughters, thus causing less external exposure of the users. With the advent of liquid-crystal display, the use of gaseous tritium light sources to illuminate digital watches is becoming increasingly common. The annual collective dose equivalent arising from radioluminous timepieces employing different radionuclides has been assessed in a number of countries. When projected to the world population this dose is of the order of 2000 man sievert.

103. *Electronic and electrical devices.* They include starters for fluorescent lamps, trigger tubes in electrical appliances, and excess voltage protection devices. Radionuclides incorporated into this equipment for better, faster and more reliable operation include krypton-85, promethium-147 and thorium-232. In spite of the very high number of these devices in operation, and the significant amounts of activity involved, the resulting doses are expected to be very low. They may however become appreciable in the event of accidental breakage and careless disposal.

104. *Antistatic devices.* These are used in industry and, in some countries, in domestic appliances to reduce the build-up of electric charge in certain materials. Polonium-210 is mainly used in these devices to ionize the air. Under normal conditions of use, the only significant hazard would result from external irradiation due to the very small gamma component emitted. Under extreme stress conditions (e.g., impact or fire) the integrity of the component parts may however be altered and a significant potential for doses arising from internal irradiation may ensue.

105. *Smoke detectors.* These appliances usually contain americium-241. In many countries they have a very large market in industrial, public, commercial and private buildings because fire experts recognize their value for the protection of life and property. Assuming a useful life of ten years for the many millions of units

[7] This subject is reviewed extensively in Annex C "Technologically modified exposures to natural radiation".

now installed, and assuming that they may be disposed of by sanitary land-fill or by incineration, the resulting collective effective dose equivalent commitment resulting from the 1978 production is found to be about 10 man sievert. Most of it results from external exposure during the useful life of the smoke detectors.

106. *Products containing uranium and thorium.* Uranium is used primarily as a pigment in ceramic and glassware. Thorium is used in incandescent mantles and in some optical products. The principal hazard posed by the utilization of these substances under normal conditions is the dose from the beta-emitting decay products, and, under special circumstances, high doses could be delivered to specific tissues. For example, fairly high doses to the lens of the eye could be delivered from optical lenses containing high percentages of thorium. Also, the dose to the oral epithelium from uranium incorporated into the porcelain used in prosthetic dentistry to simulate the fluorescence of natural teeth could be high.

107. *Television sets.* During normal operation, television sets give rise to soft x rays from which external exposure may result. However, the x-ray emission from recently built colour television receivers is negligible under conditions of normal operation and appropriate servicing.

(d) Radon and its decay products[8]

108. It has become increasingly evident that a very important contribution to exposure from natural sources results from radon-222 (usually called radon) and its decay products. Another naturally-occurring radioactive isotope, radon-220 (usually called thoron), also contributes some dose. These facts prompted the Committee to investigate in depth the exposure to these gases and to examine the most important physical and physiological variables influencing the exposure.

109. Radon and thoron are naturally-occurring radioactive gases, products of the uranium and thorium decay series, respectively. Uranium and thorium occur in nature as primordial elements in rocks. By diffusion, a small proportion of the radon and thoron produced leaks out of these materials and is dispersed in ground water and in air where these radionuclides may be found in varying concentrations. Radon and thoron decay to their numerous daughters until the uranium and thorium series are completed by stable isotopes of lead.

110. The Committee has considered the mechanisms of radon and thoron release from their natural sources and the variables influencing this release (particle size of the rocks, porosity, humidity); the mechanisms of diffusion of these gases to the surrounding water and air; the transfers of radon and thoron through soil and their exhalation to air; the dispersion in air of these gases and their decay products; and the influence of the vertical temperature gradient, the wind strength and the turbulence of air on such dispersion. Because of the short half-life of thoron (about one minute), this gas is only to be found within a few tens of metres above the ground, while radon, with a half-life of approximately four days, reaches an altitude of several kilometres. The geographical location and the prevailing meteorological conditions affect the concentration of these nuclides at ground level, with pronounced seasonal variations. Usually air masses above continental regions have the highest concentrations, while air masses above the oceans or the artic regions have the lowest concentrations. Mean annual values of radon concentration in outdoor air at ground level vary between 0.1 and 10 becquerel per cubic metre. A typical value in populated areas is 3 becquerel per cubic metre.

111. Because of the rapid diffusion of radon in the atmosphere, the activity concentration of the radon daughters in ground level air shows in general a deficiency in comparison with the radon concentration. The equilibrium factor between radon and thoron and their daughter products is a measure of this deficiency. The equilibrium factor depends on many other conditions, such as the decay constants of the various daughters, the concentration and size distribution of the aerosol particles in the air, the deposition of these aerosols on the surrounding surfaces and the air exchange rate. All these conditions may be investigated experimentally. For practical purposes it is important to point out that low ventilation rate in confined spaces may result in high exposure to radon and thoron decay products.

112. The concentration of radon in water may vary from practically zero to values of up to about 100 megabecquerel per cubic metre in some waters. The radiation doses caused by radon in drinking water are due partly to ingestion but mostly to inhalation of the radon daughters produced by decay of radon released from the water. Approximate calculations of the relative doses resulting from a given radon concentration in drinking water are possible. However, owing to the fact that reported measurements were often carried out in areas known for their high content of uranium or radium, such values cannot readily be considered representative of mean values applying to a whole region or to an entire country. Available information shows that the dose of radiation delivered by radon in drinking water is not usually a major problem for exposure of the general population, except for some cases in which, owing to special geological conditions, the radon content is particularly high.

113. Since most of the radiation dose from radon is received by man while living indoors, the Committee has reviewed a large body of data on the measured concentrations of radon and thoron and their decay products in houses in different parts of the world. These concentrations, normally of the order of 20 becquerel per cubic metre, are higher than for outdoor air. Very high indoor concentrations may result from low rates of ventilation, or from elevated radon levels due to high radium content in the building materials or in the soil under the house, or from the use of radium-rich water. Under adverse conditions peak values of 10 000 becquerel per cubic metre of air, or more, may be found.

114. Radon daughters give rise to exposures in mines. The review of the Committee has considered measurements in many different mines and countries. It has shown that, depending on the type of rock and on the conditions of ventilation, concentrations to be found in uranium mines are usually less than 1000 becquerel per cubic metre of air. However, in some unventilated sections of the mines concentrations of up to 1000 times higher may occur. In non-uranium mines average concentrations are about the same but ventilation requirements to achieve such values are less stringent.

[8] This subject is reviewed extensively in Annex D "Exposures to radon and thoron and their decay products".

115. Irradiation from radon and thoron decay products arises from inhalation and takes place in the respiratory tract. The actual dose delivered to the various anatomical structures depends on the relative fraction of attached and free daughter products, on the size of the aerosol particles to which they are attached and on pulmonary function. On the average, the dose from radon daughter products to the bronchial basal cell layer is a factor of 5 to 8 times higher than the dose to the pulmonary region. Using weighting factors for the regional distribution of the lung dose and the mean lung dose, the relevant effective dose equivalent may be calculated. Global averages of the annual effective dose equivalents caused by inhalation of radon and thoron and their decay products are given in Table 2. Values in temperate and tropical regions are estimated to be about 25% higher and 70% lower, respectively, than these global averages. It should be pointed out that, in temperate latitudes, the dose indoors is about 15 times higher than outdoors, both because concentrations of the radioactive gases are higher inside the houses and because people usually spend more time inside than outside.

TABLE 2. GLOBAL AVERAGES OF THE ANNUAL EFFECTIVE DOSE EQUIVALENTS (MILLISIEVERT) CAUSED BY EXPOSURE TO RADON AND THORON DAUGHTERS THROUGH INHALATION UNDER VARIOUS CONDITIONS

Condition	*Radon daughters*	*Thoron daughters*[a]
Outdoors[b]	0.06	0.02
Indoors[b]	0.7	0.15
Uranium mines[c]	~15	

[a] Based on limited data.
[b] The occupancy factor was taken to be 0.8 indoors and 0.2 outdoors.
[c] Applies to years 1977–1979.

116. In view of the importance attached to the development of energy conservation programmes, the Committee has outlined some general considerations on the possible increase in effective dose equivalent due to radon daughter inhalation that may arise as a consequence of such programmes. Decreased ventilation in factories, and particularly in mines, could enhance substantially the values of the collective effective dose equivalent of workers. In houses, decreased ventilation would also lead to a dose increase—and therefore presumably to health consequences—depending on the type of house, its location, the type of heating, ventilation and other factors. The Committee has outlined the basic principles for the assessment of the radiological impact of such energy conservation measures.

3. Exposures resulting from nuclear explosions[9]

117. Although nuclear explosions in the atmosphere have diminished from the intensity of 1954 to 1958 and 1961 to 1962, occasional testing in the atmosphere still occurs. All these explosions are the cause of a continuing exposure of the world population to radioactive fallout. It is estimated that the exposures from all nuclear tests conducted through 1980 is equivalent to about four years of additional exposure of the present world population to the natural radiation background. Much of the exposure from fallout activity will be delivered at low rates for years into the future. Each new atmospheric test commits present and future generations of mankind to some radiation exposure.

118. The Committee has continued to assess the exposures to which the population of the world has been subjected from the release to the environment of radioactive materials produced in nuclear explosions. Such explosions have been carried out in the atmosphere since 1945. Intensive nuclear testing programmes were conducted in the years 1954 to 1958 and 1961 to 1962. Further explosions occurred to the end of 1980, although no tests were conducted in 1979 and 1981. The Committee has not reviewed exposures from any small emissions which might be associated with underground tests.

119. Radioactive debris from nuclear explosions enter the tropospheric and stratospheric regions of the atmosphere, the partitioning depending on the location and yield of the explosion. The Committee has presented estimates of the amount of radioactive materials produced in atmospheric nuclear testing, the dispersion in atmospheric regions and the deposition of the debris onto the earth's surface. The pathways leading to irradiation of man, including inhalation of contaminants in air, ingestion of radionuclides in diet, and external irradiation from activity in soil, have been considered in evaluating exposures.

120. The 1977 report of the Committee contained estimates of the dose commitments to the world population from nuclear tests conducted prior to 1976. This report updates such estimates to the end of 1981. The Committee has evaluated separately the dose commitments to the populations of the northern and southern hemisphere and the average value for the world. Dose estimates are higher for the northern than for the southern hemisphere, since most of the testing and thus most of the deposition took place in the northern hemisphere.

121. A summary of the Committee's findings is given in Table 3, which presents the effective dose equivalent commitments from nuclear testing to the populations living in the north and south temperate zones and in the whole world. The most significant pathway is through ingestion, largely due to carbon-14, caesium-137 and strontium-90, followed by external irradiation due to caesium-137 and several other short-lived radionuclides. The collective effective dose equivalent commitment due to the tests conducted in the atmosphere up to the end of 1981 is 3 10^7 man sievert. This value, which takes into account an estimated future growth of the population of the world, is equivalent to about 4 years of present exposure of the population to natural sources. Most of the collective effective dose equivalent commitment can be attributed to the test

TABLE 3. SUMMARY OF EFFECTIVE DOSE EQUIVALENT COMMITMENTS AND PATHWAY CONTRIBUTIONS FROM NUCLEAR EXPLOSIONS IN THE ATMOSPHERE CONDUCTED TO THE END OF 1981

Location	*Effective dose equivalent commitment (millisievert)*	*Pathway contribution (%)*		
		Ingestion	*External irradiation*	*Inhalation*
North temperate zone	4.5	71	24	5
South temperate zone	3.1	90	8	2
World	3.8	79	18	3

[9] This subject is reviewed extensively in Annex E "Exposures resulting from nuclear explosions".

programme that took place in 1961 and 1962 (580 days and 370 days of present exposure of the world population to natural sources, respectively). The per caput annual dose reached a peak in 1963 corresponding to about 7% of the average annual exposure to natural sources; in 1966, this figure had decreased to about 2% and it is at present less than 1%.

122. Twenty-one radionuclides were considered by the Committee in these evaluations. Of these, only 4 contribute more than 1% to the collective effective dose equivalent commitment of the world population. In decreasing order of importance these nuclides are: carbon-14, caesium-137, zirconium-95, strontium-90. For zirconium-95, its contribution to the global population dose committed by tests up to 1981 is already largely completed. For caesium-137 and strontium-90, a large part of the dose commitments will have been delivered by the end of this century. Only carbon-14 will continue to contribute doses into the far future, though at low dose rates, due to its long decay half-life. The long-lived decay products of the actinides may also have to be taken into consideration in the long term, but preliminary indications are that they deliver at very low rates an additional contribution of the order of 0.1% to the total effective dose equivalent commitment.

123. The assessments of doses due to radioactive fallout contained in this report are only marginally different from those reported in the past, because of the relatively small amounts of activity released from the fewer nuclear explosions in recent years. The present dose assessments are however more complete, as additional nuclides and other possible transfer pathways have been considered, the transfer factors have been re-evaluated, and the dose estimates extended to more recent measurements of radioactive fallout. There are still some uncertainties concerning both the measurements and the modelling. It can be reasonably expected that further knowledge may lead in the future to minor adjustments and improvements in the Committee's assessments.

4. Exposures due to nuclear power production[10]

124. The collective dose commitment arising from environmental contamination due to reactor operation provides a relatively minor contribution to the total radiological impact of the nuclear fuel cycle. Uranium mining and milling, through the emanation of radon and its daughter products from the tailings of the mills, is one important contributor to the collective dose commitment. The dose commitment from nuclear power, assuming present technology, would be expected to increase with the increase in installed nuclear capacity. The utilization of plutonium in either recycling or fast breeding reactors or other advanced fuel cycle technologies would substantially decrease the collective dose commitment per unit energy generated.

125. The number of nuclear reactors in operation for the generation of electric power has increased since the previous report of the Committee to include, in 1979, 235 reactors in 22 countries, with a total installed nuclear generating capacity of about 120 gigawatt of electrical energy [GW(e)]: this represents a doubling of installed nuclear plants over the period 1975 to 1979 covered by the Committee's report. Projections to the year 2000 are somewhat uncertain but they are at present within a range of 1000–1600 GW(e), which is about two-thirds of the capacity projected in the previous report for the same year. Revised estimates in many countries confirm that the increase in generating capacity will be smaller than previously predicted.

126. The nuclear fuel cycle includes many steps, as follows: mining and milling of uranium ores; conversion to various chemical forms; enrichment of the isotopic content of uranium-235 (in some cases); fabrication of the fuel elements; production of power in the nuclear reactors; reprocessing of irradiated fuel and recycling of fissile and fertile nuclides recovered (in some cases); transportation of nuclear materials between installations at various steps of the fuel cycle; and, finally, disposal of radioactive wastes. Although almost all of the artificial activity associated with the production of nuclear power is present in the irradiated nuclear fuel, at each of the above steps of the cycle, releases of small amounts of radioactive materials to the environment occur. Most of these releases, in view of the short half life of the radionuclides and of their limited environmental mobility, are only of local or regional concern. However, some radionuclides having very long half-lives or rapid environmental dispersal, are distributed globally and may contribute to the irradiation of man and the environment on a world-wide scale.

127. For each step of the nuclear fuel cycle the Committee has evaluated the doses to members of the public resulting from releases of radioactive materials. The Committee's assessments have been derived in terms of collective absorbed dose commitments per unit energy generated, that is in terms of man gray per GW(e) year. The models through which absorbed dose commitment to various body organs or tissues may be converted to effective dose equivalent commitment per unit electricity generated have been extensively discussed in Annex A.

128. Because environmental releases from nuclear installations are subject to technical control, doses to individual members of the public are usually kept well below the recommended limits. There are four groups of people exposed to these types of sources: those irradiated on account of their work in the plants; the local population residing within a few hundred kilometres of the plants; the regional population within a few thousand kilometres; and, finally, the whole world population. Only the last three groups are examined here, since the occupationally exposed individuals are treated separately in Annex H.

129. Since the concentrations of the effluents from the nuclear installations are low at the point of release and extremely low in the surrounding environment, models must be used to estimate the doses to populations over long distances from the plants and over long periods of time. The values of the transfer parameters of the various radionuclides in these models are derived from environmental monitoring results and from experiments of various types. The most important starting point of these models is the amount and type of radioactive material released from various nuclear installations. This information was available to the Committee essentially up to the year 1979 and was converted to average releases per GW(e) generated between 1975 and 1979. Such average values do not apply to any particular installation and they reflect

[10] This subject is reviewed extensively in Annex F "Exposure resulting from nuclear power production".

differences in reactor design and changes in the rates of release between new and old reactors. Although normalized release rates are deemed to be representative of the current situation for nuclear power production around the world, they should not be extrapolated to future practices or to particular plants without great caution and appropriate corrections.

130. In order to estimate collective dose commitments corresponding to the above-mentioned normalized releases, the Committee used for its assessments hypothetical sites whose location characteristics are broadly representative of each major stage of the fuel cycle, namely, mining and milling, fuel fabrication, reactor operation and reprocessing. The Committee also assumed that the environment receiving the releases from each model plant would be a hypothetical environment containing the main features of existing sites and enabling calculations of dose to be made for the most common pathways of transfer to man of the released radionuclides. It should be stressed that such broad generalizations intended to produce estimates on the overall impact of nuclear installation around the world are not representative of any one site. Site-specific calculations would need data on the specific releases, the local and regional environmental characteristics and the actual pathways of radionuclide transfer to man.

131. Calculations of the collective dose commitment require that the instantaneous dose rate absorbed in any organ or tissue be summed over the whole period of exposure. This operation may be difficult and the Committee made use of approximations concerning the size of the world population and the dietary and other habits of the exposed individuals which were assumed to be stable over the period during which the summing operation was carried out. Using these major assumptions, the Committee reviewed the various steps of the nuclear fuel cycle and calculated the dose contributions to the public from the various nuclides and irradiation pathways applicable to each source of exposure.

132. Finally, the Committee made an attempt to estimate the collective effective dose equivalent commitment to the public from nuclear power production. As outlined in Annex A, these figures are indicative of the overall health detriment incurred by mankind from this source of exposures, under the assumptions specified. In Table 4, the values of this quantity are normalized to one GW year of electrical energy produced. Within the next 100 years the total will be about 20 man sievert per GW year, although additional exposures at low annual rates will occur over very long periods of time. Table 4 indicates how the collective doses committed per GW year accumulate with time up to 10 000 years.

TABLE 4. ESTIMATES OF THE COLLECTIVE EFFECTIVE DOSE EQUIVALENT COMMITMENT (MAN SIEVERT) TO THE PUBLIC FROM THE PRODUCTION OF NUCLEAR POWER, NORMALIZED TO ONE GW YEAR OF ELECTRICAL ENERGY PRODUCED, AND THEIR ACCUMULATION WITH TIME

	Fuel cycle operation (excluding tailings and waste disposal)			
Years	*Local and regional*	*Global*	*Mill tailings*	*High-level waste disposal*
10^2	6	12	< 3	0
10^4	6	70	<500	0

133. No estimates are given in Table 4 for periods exceeding 10 000 years, when radon emanating from mill tailings and iodine-129 from reprocessing plants or spent fuel repositories are likely to be the dominating sources. For such periods the Committee's conservative methods of calculation would have led to higher values of collective dose equivalent commitment, not exceeding a few thousand man sievert per GW(e) year under the headings "global" and "mill tailings" combined, and not higher than a few tens of man sievert per GW(e) year under the heading "high-level waste disposal". However, the uncertainties associated with assessments of dose in the far future and the limited usefulness of those assessments are not easily summarized. The reader is referred to Annex F, especially paragraphs 194–201 and paragraphs 207–212 of that Annex, for further discussion.

134. The local and regional contribution from fuel cycle operations is estimated to be 5.7 man sievert per GW(e) year; of this 0.5 is due to mining, milling and fuel fabrication, 4.2 to the reactor operation, and 1.0 to fuel reprocessing. Ninety per cent of this dose commitment is delivered in the year following discharge and the remainder over the next few years. For those nuclides which become globally dispersed, the collective dose commitment is 670 man sievert per GW(e) year, 90% being delivered in the period between 10^4 and 10^8 years from discharge. For all of these future estimates the figures are uncertain. This applies especially to mill tailings, because different management practices or climatological changes could reduce the values by several orders of magnitude. Also, the introduction of fast breeder reactors may reduce uranium ore requirements by two orders of magnitude, which would affect the dose commitment from tailings by the same factor. Other advanced fuel cycle technologies could achieve substantial reductions.

135. Available studies on the dose commitment resulting from the disposal of high-level radioactive wastes in deep geological formations indicate that up to several thousands of years this contribution is negligible, by comparison with the other sources. For periods in excess of ten thousand years the relevant dose may only reach about 0.1–1% of the total normalized dose commitment from nuclear power production.

136. In order to estimate the maximum per caput or average annual dose in the future as a result of nuclear power production, an incomplete collective dose commitment must be used which is here taken at 500 years. The releases during the operational stage of the nuclear fuel cycle lead to a local and regional collective effective dose equivalent commitment which is all received in this period. For those nuclides which become globally dispersed, the incomplete collective dose commitment to 500 years is 18 man sievert per GW(e) year. The choice of 500 years as a mean duration of the practice of producing power by nuclear fission implies the use of breeder reactors which would decrease the rate of mining. The incomplete collective dose commitment from mining and milling, based on the present fuel cycle, is therefore taken to 100 years and is likely to be due only to radon releases, giving 2.5 man sievert per GW(e) year. Thus, on the pessimistic assumptions that no technological improvements are made and current levels of discharge continue for 500 years, the maximum annual collective dose would be about 25 man sievert per GW(e) year. The annual collective and per caput doses for a notional nuclear

programme to the year 2500 are shown in Table 5, again assuming that present release levels are not reduced and that the generation of electric power reaches some 10^4 GW(e) year in 2500. It can be seen that even with the maximising assumptions made here, the level of the annual per caput dose due to effluent releases would rise to the equivalent of 1% of the average exposure to natural background radiation. After the end of the practice, the per caput doses would reduce to about 1% of the final values after 100 years.

TABLE 5. ANNUAL PER CAPUT DOSES FROM THE CONTINUED GENERATION OF NUCLEAR ELECTRIC POWER TO THE YEAR 2500

Item	*Year* 1980	2000	2100	2500
Annual projected nuclear generation (GW[e]a)	80	1 000	10 000	10 000
Annual collective effective dose (man sievert)	500	10 000	200 000	250 000
World population (billion people)	4	10	10	10
Annual per caput dose (microsievert)	0.1	1	20	25
Percentage of average exposure to natural sources of radiation (%)	0.005	0.05	1	1

137. Attention should again be drawn to the fact that extrapolation into the future is very uncertain and to a large extent speculative: for example, over the last decade the development of new concepts in radiation protection, better design criteria for the new plants, and technological improvements in the old plants, have resulted in a decrease of the releases to the environment, in spite of an increased electrical output of the plants.

138. The Committee carried out a first attempt to evaluate the collective dose commitment arising from the accidental release of radioactive materials, on the basis of two major accidents for which data on the irradiation of the public and the environment were available. It proved impossible, on the basis of these two accidents, to evaluate retrospectively the component of the collective dose commitment due to accidental release of radioactivity in nuclear power programmes.

5. Occupational exposures[11]

139. The Committee revised its estimates of average doses to various groups of workers and the collective doses from various occupations. The methodology developed in the previous report for extracting parameters from dose distributions useful for comparisons has been refined. Through this analysis the Committee was able to assess collective doses from a number of occupations and identify several groups of workers for whom the average exposures are higher than for other groups. The absolute value of these doses may vary from one installation to another and between workers performing similar operations in different countries. However, for routine operations, the difference in dose levels is generally no more than 50 per cent of the authorized dose limits.

[11] This subject is reviewed extensively in Annex H "Occupational exposures".

140. As in the past, the Committee updated and analysed the existing information on the radiation exposure of various categories of workers, incurred as a result of their occupation. Knowledge of data on occupational exposure, both individual and collective, is required to evaluate trends in the doses delivered by various practices; to assess the level of individual risks for radiation workers for comparisons with the risks of other occupations; and to assess the total radiological impact per unit practice on the population from different sources. Differences in general methods for monitoring exposed workers in various countries, as well as technical difficulties, contribute to the inhomogeneity of the data available and limit their usefulness to some extent. However, the Committee believes that a judicious analysis of the existing information may still be very valuable, and at least may provide some objective preliminary background for the above needs.

141. In the previous report the Committee suggested certain parameters of a dose distribution which would be useful for comparison and proposed a reference distribution solely for the purpose of intercomparison. The log-normal form of the distribution was meant to reflect the fact that in many occupations involving radiation exposure the majority of workers receive low doses and only a few are exposed to relatively high doses. Such a reference distribution has attracted inappropriate attention, so that the Committee has now revised its techniques of analysis to permit direct comparisons of dose distributions with a standard range of values. The parameters selected for intercomparison are the annual collective dose; the average dose, which depends on the number of workers included; and the proportion of the collective dose delivered at annual individual doses exceeding a certain level, taken as 15 milligray. The increasingly wide acceptance of this method of analysis is evidence of its usefulness and the Committee would like to stress the need to report doses in a manner which might improve such analyses.

142. The work of the Committee covered several different classes of occupational exposure. In relation to the nuclear fuel cycle, systematic consideration was given to the workers exposed in mining and milling operations, in fuel manufacture, in various operations with nuclear power reactors, in fuel reprocessing, and in reactor research and development. An increasing amount of information is becoming available on these subjects and higher doses to large groups of individuals are to those involved in uranium mining. It is also possible to calculate the radiation doses per unit practice. Thus, the total annual collective dose equivalent for workers in all the above operations is calculated to be about 30 man sievert per GW year: the more detailed breakdown in Table 6 shows that reactor operation and fuel reprocessing contribute by far the largest proportions of the occupational doses. On the whole, the data show no striking departure from previous assessments of the Committee. However, it is difficult to separate out the research which is specifically directed to the nuclear fuel cycle and therefore a precise evaluation of this component is not possible; the indications are that it represents lower doses per unit practice than reported earlier. Taking the energy generated by nuclear power in 1979 to be 70 GW year, the occupational collective dose in that year is about 2000 man sievert.

143. Other classes of occupational exposure examined were those involving medical and industrial uses, and

TABLE 6. SUMMARY OF COLLECTIVE EFFECTIVE DOSE EQUIVALENTS PER UNIT ENERGY GENERATED DELIVERED TO WORKERS ENGAGED IN DIFFERENT PARTS OF THE NUCLEAR FUEL CYCLE

Operations	*Collective effective dose equivalents per unit energy generated (man sievert per GW[e] year)*
Mining and milling	1
Fuel fabrication	1
Reactor operation	10
Fuel reprocessing	10
Nuclear research	5
TOTAL	~30

research and development using radiation and radionuclides. Although the individual doses received by medical workers may be significant, the overall contribution is relatively small. An indication of this may be derived from the annual collective dose equivalent per million population; this varies from country to country, but a reasonable value for countries with a high standard of medical care is of the order of 1 man sievert per million people. Some situations have been identified in industrial uses of radiation where more information is needed, especially for industrial radiographers. Other large groups exposed are aircrew and non-uranium miners. The total impact of all these uses, together with non-nuclear power research, is about 1.5 man sievert per million people.

144. The Committee collated and analysed information brought to its attention on the subject of accidental irradiation of occupationally exposed people. The data showed consistently that industrial radiographers, particularly those handling mobile sources, were the category most exposed to accidents. Mishandling of sources and equipment, coupled with a high incidence of equipment failure, inadequate training and human errors appeared to be among the most common causes for these accidents. Some criticality accidents resulting in several fatalities were reported in the early days of nuclear power development. The overall number of incidents and accidents reported appears very small considering the number of people using radiation or radioactivity in their work, but the distribution of accidents between different types of work is highly non-uniform.

145. The Committee has made a number of recommendations concerning areas where more analysis of data is required to extract pertinent information; particularly with regard to the pattern of accumulation of dose over a working lifetime, this could most usefully be done by those gathering the data. If these recommendations are acted upon there should be a much clearer indication of the overall occupational exposure situation in all areas of work within a few years.

6. Medical exposures[12]

146. Medical exposures are characterized by high dose rates and very uneven distributions of dose. The latter fact makes the use of concepts such as the effective dose equivalent helpful, but this concept has substantial shortcomings when applied to patients. Nevertheless, a cautious application of effective dose equivalent indicates that the relative detriment from various types of medical examinations could be different from that given in previous reports where the main emphasis was on the genetically significant and the mean marrow doses. Preliminary information concerning radiological practices in some developing countries points to the conclusion that two-thirds of the world population live in countries where the frequency of radiological examinations appears to be an order of magnitude lower than in developed societies.

147. An important contribution to the global collective dose takes place in the course of radiological procedures. Medical exposure gives the largest man-made contribution to the radiation doses received by the population and in some industrialized countries this contribution approaches the doses received from natural sources. The main difference between this and other sources of exposure is that the individuals receiving the doses are usually the same individuals who are expected to benefit directly from the procedures involving irradiation.

148. Radiation is used in medicine for diagnostic purposes or for the treatment of diseases, particularly cancer. The doses received by the patients are extremely variable: from very low, as in many diagnostic examinations, to very high, as in radiotherapy. Although all individual doses contribute to the collective dose received by the population at large, the bulk of this collective dose comes from the small doses involving many individuals, rather than from the high doses delivered to relatively few radiotherapy patients.

149. The scope of the Committee's analysis of exposure levels in the course of medical examinations or treatments is very wide. First, the Committee considers that knowledge of individual and collective medical exposures is necessary to place these into the appropriate perspective with respect to the other sources of human radiation exposure. Secondly, there is a need for analyses of the doses to individual organs—and of the range of their variability—for various types of radiological examinations, in order to know and compare the risk of selected practices. Finally, it might be possible from such a review to identify groups of patients exposed to high doses that could be followed in the future through epidemiological studies for improved assessments of the incidence of unwanted radiological sequelae.

150. In view of the magnitude of the medical exposure component, and of the great potentiality for its significant reduction, the Committee has repeatedly reviewed the relevant information in order to monitor the trend closely. The earlier reports were particularly focused on the doses delivered to the gonads, to derive assessments of the possible genetic risk of exposures through the so-called genetically significant dose. More recently, the doses received by other organs were also given increasing attention, in order to identify the medical procedures resulting in particularly high organ doses. The Committee followed this same trend in the present report.

151. The Committee reviewed available information on the total frequency of diagnostic x-ray examinations, indicating that their rate may vary between 300 and 900 examinations per thousand inhabitants per year in industrialized countries, excluding mass surveys and dental examinations. Examinations of skeleton and

[12] This subject is reviewed extensively in Annex G "Medical exposures".

thorax were seen to be the most frequent in many countries. A special effort was made to survey the state of diagnostic radiology in developing countries, with the collaboration of the World Health Organization, by collating information on the population coverage of radiological services. It was found that equipment was scarce and unevenly distributed in these countries, with the rural population having limited access to the existing facilities. In industrialized countries a pronounced tendency in a reduction of the individual exposures was documented for some types of examinations such as dental radiography and mammography.

152. Absorbed doses in various organs and tissues of interest to the Committee were in the range of less than 0.01 to 50 milligray per examination, considering all types of radiodiagnostic examinations. Special attention was given to certain x-ray examinations, for various reasons: either because they are very common and could contribute therefore substantially to the collective dose (e.g., dental examinations); or because they involve exposure of tissues of known high susceptibility to cancer induction by radiation (e.g., mammography). In both of these cases a trend towards a decrease of the doses delivered in the course of a single examination was documented, due to the improved technical conditions of exposure.

153. In two developed countries the collective effective dose equivalent for diagnostic radiology has been reported as about 600 and 1800 man sievert per million people. In the absence of any other data, the Committee has tentatively, for the purpose of this report, used the round number of 1000 man sievert per million population as the annual collective effective dose equivalent for developed countries, which corresponds to about 50 per cent of the exposure to the natural radiation sources. The corresponding value for developing countries may be an order of magnitude lower, so that a weighted figure for the whole world could be in the region of 400 man sievert, or about 20 per cent of the average exposure to natural sources.

154. Nuclear medicine examinations contribute, on the whole, relatively little to the exposure of the population from medical sources, by comparison with x-ray diagnostic procedures. The value of the collective effective dose equivalent would, however, be expected to be highly variable owing to the differences in radiological practice in various countries and to the variable spectrum of diseases of the different populations. For radiotherapeutic exposures, the Committee analysed data collected by IAEA and WHO on the availability and use of radiotherapy equipment in many countries. They show, at the same time, a general tendency towards an increase in the services and a very unequal distribution between developed and developing countries.

155. With regard to the genetically significant dose equivalent, the Committee believes that a rough estimate that may apply to developed countries for which some information is available is about 0.1–0.2 millisievert per year, all components of the dose received in the course of medical practices being taken into account. The corresponding figures for developing countries would be about an order of magnitude lower.

156. The Committee would like to express the wish that statistics for medical irradiation may in the future be reported in such a way to allow a more precise evaluation of the above quantities.

7. Summary and conclusions

157. In this report, the Committee used various quantities to evaluate the exposures from the radiation sources it has reviewed. The individual effective dose equivalent rates have been used to show the variability of the individual exposures according to location, occupation, time or other factors. By adding all the individual effective dose equivalent rates, the collective effective dose equivalent rates have also been obtained, which express for a given time the radiation impact resulting from a given source or practice.

158. It is of interest to study the variation in time of the collective effective dose equivalent rates over the last few decades. Figure II(a) presents the contributions of the exposures from medical uses of radiation, nuclear explosions in the atmosphere and nuclear power production, expressed as a percentage of the average exposure to natural sources. The values for medical irradiation and nuclear power production include the exposures of the workers as well as those of members of the public. It is estimated that the contribution of medical exposure has not changed appreciably over the years, while the contribution of nuclear explosions has followed a discontinuous trend but has mostly decreased since 1963, with small variations due to more recent explosions. The annual collective effective dose equivalent attributable to the production of electrical energy by nuclear means has been increasing continuously, due to the expansion of nuclear power programmes, although its contribution is at a substantially lower order of magnitude.

159. In spite of the many uncertainties, most of the values in Figure II(a) are unlikely to be in error by orders of magnitude and therefore lend themselves to some general considerations. Among the various sources of radiation, the natural sources with an average annual effective dose equivalent of 2.0 millisievert are by far the most important.

160. With respect to the man-made sources, the highest contribution comes from the medical uses of radiation, particularly for diagnostic purposes. The average annual effective dose equivalent from medical uses of radiation throughout the world is taken to be about 0.4 millisievert, which corresponds to approximately 20% of the average annual exposure to natural background. The Committee believes that there is a good potential for dose reduction, compatible with the objective of the practices. Since this dose is relatively high, the corresponding gain would be expected to be great.

161. Summing the collective effective dose equivalent rates over time leads to the collective effective dose equivalent commitments which are assumed to be proportional to the total health impact from a given source or practice. The sources or practices could be, for example, the nuclear explosions in the atmosphere conducted so far; or one year of power production by nuclear fission at the present time; or the extraction of one tonne of phosphate ore. The global collective effective dose equivalent commitments are the most convenient quantities in order to compare the expected detriment from the exposure to different radiation sources.

162. In the 1977 report the Committee adopted a table to summarize its global dose estimates in which the whole-body dose commitments from different sources

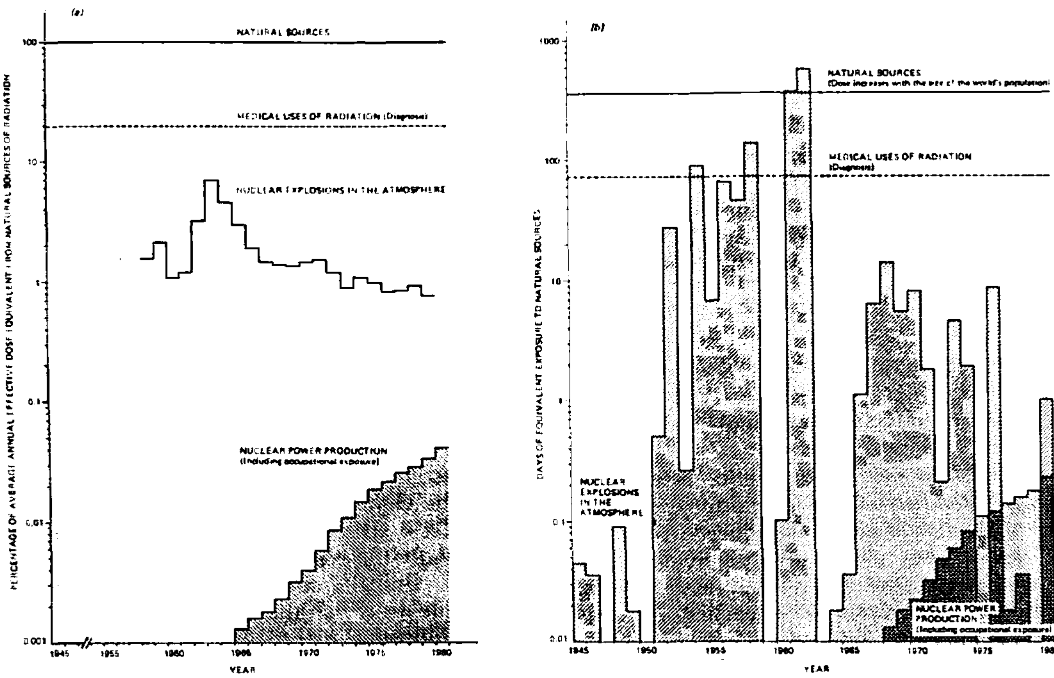

Figure II. Trends with time of doses from different sources of radiation. (a) Annual effective dose equivalents, expressed as percentage of the average exposure to natural sources; (b) Collective effective dose equivalent commitments per year of practice, expressed as days of equivalent exposure to natural sources

were expressed in terms of the duration of exposure to natural radiation of the world population which would cause the same dose commitment. This format of presentation received widespread attention because it allows comparison of the different sources on an easily appreciable scale of time. The Committee has therefore updated some of the relevant estimates, comparing the global collective effective dose equivalent commitments, expressed in days of exposure to natural sources. Figure II(b) presents, on a semi-logarithmic scale, estimates of such collective effective doses that were committed by the use of radiation for medical diagnostic purposes, by nuclear test explosions and by the production of nuclear power in each year from 1945 to 1980. These collective dose commitments are expressed as the number of days of exposure to natural background that would give the same dose. The doses from natural and medical irradiation are assumed by the Committee to have remained constant.

163. The collective effective dose equivalent commitments per year of atmospheric tests reached a peak in 1962 corresponding to about 1.6 year of natural background; since that time the annual commitments have been substantially lower. The collective effective dose equivalent commitments per year of nuclear power production have been steadily increasing up to the present time.

164. Two considerations should be stressed to avoid possible misconceptions about the content of Figure II(b). Firstly, the presentation of the exposures from the various sources in the same graph is simply to be regarded as one way of representing the relative contribution to the global effective dose equivalent commitment. It does not imply any judgement from the Committee as to the justification of the various sources or practices on ethical, social or economic grounds. Secondly, such presentation would be misleading if the many qualifications discussed in the preceding paragraphs of this report and in all its scientific Annexes were not taken into account.

165. The collective effective dose equivalent commitment resulting from all nuclear explosions that have taken place up to the end of 1980 corresponds to about 4 years of natural radiation exposure (Figure II(b)). About 10% of the collective effective dose equivalent commitment has already been delivered; the remaining fraction, mostly due to carbon-14, will be delivered in the next ten thousand years or so.

166. Averaged over the whole world, the collective effective dose equivalent commitment (truncated to 500 years) due to one year's production of nuclear power at the 1980 level of installed capacity of 140 GW(e) corresponds to approximately 5 hours of natural radiation exposure (Figure II(b)). This estimate includes the exposure of the workers as well as that of the public. While the long-term component of the global dose to members of the public may to a first approximation be regarded as uniformly distributed within the time of delivery of the dose, the short-term component is spread non-uniformly around nuclear installations. The Committee has analysed the extent of such non-uniformity and has thus indirectly pointed out the conditions for further improvement of the present situation through national or international actions. On the assumption that there would be no change in the collective dose commitment per unit practice, one year of energy production, at the projected installed nuclear capacity of 1000 to 1600 GW(e) by the year 2000, would result in a global dose equivalent commitment (truncated to 500 years) of about 2 days of background radiation exposure, including the occupational component. This assumption could however be unrealistic because of technological developments and the evolution of regulatory actions.

167. The total collective effective dose equivalent commitment due to the production up to the present time of electrical energy by nuclear fission is roughly estimated to correspond to 1 day of average exposure to natural background (Figure II(b)). This value is truncated to 500 years and includes the exposure of workers and of the general public.

168. Other sources of radiation give rise to much lower collective effective dose equivalent commitments and require no special comment.

169. The situation depicted calls for further review at appropriate intervals of time, in order to keep the trends under surveillance, to ascertain possible deviations of the predicted values, and to refine the estimates further. Detailed studies on selected subjects rather than comprehensive assessments may be particularly appropriate for the time being.

C. RADIATION EFFECTS

1. Genetic effects of radiation[13]

170. New experiments on the genetic effects of radiation have provided further scientific information for the assessment of the risk of radiation-induced hereditary diseases in man. They have also increased the Committee's confidence that the general assumptions, and the estimation procedures used earlier for this purpose, remain valid in the light of current knowledge. They have not led to any substantial change in the previous estimates of genetic risk.

171. It is well established that a significant proportion of all conceptions is genetically abnormal, i.e., carries a spontaneously-arising hereditary defect. The most severe changes in the genetic make-up are incompatible with life and lead to abortions. It has been estimated that about one-half of all clinically diagnosed spontaneous abortions have an abnormal genetic constitution. Some genetic changes are however compatible with life, but the individuals carrying these show abnormalities (ranging from severely handicapping diseases and disabilities to fairly mild conditions) at some stage of their life after birth. Surveys of populations have shown that roughly 10% of all live-born children carry some type of genetic or partially genetic defect of different grades of severity.

172. It is also well known that many toxic agents, and ionizing radiation in particular, are capable of increasing the incidence of inherited harmful conditions. When radiation interacts with the genetic material of the germinal cells in the testis or in the ovary, damage to this material may ensue. If this damage is then transmitted to the descendants of the irradiated person, it may give rise to a variety of clinical conditions which, as in the case of the spontaneously-occurring ones, may cause considerable hardship to the affected persons, their family or society in general. It is therefore very important to assess the degree to which the spontaneously-occurring genetic defects may be increased through exposure to radiation.

173. Arbitrarily, radiation effects on the genetic material may be grouped according to their nature into two different classes, gene mutations and chromosomal aberrations. Gene mutations are heritable alterations of the elementary units of heredity, which are called genes. These are further operationally classified into dominant mutations, when their effects are expressed in the immediate offspring of the individuals in whose germ cells they arose or were induced; and recessive mutations, which may not manifest themselves in the immediate progeny and are expressed only when an individual receives the same mutated gene from both the parents. In humans, as in all outbreeding species, the probability of such an event is small, except when parents are related. Thus, recessive mutations will be transmitted unnoticed from generation to generation and will persist in the population until, by chance, two individuals carrying the same mutated gene will produce progeny and the recessive mutations that arose (or were induced) earlier will become manifest. Most gene mutations do not fit precisely into one or the other of the above two categories; in fact, where it has been possible to study effects in detail, mutations of all grades ranging from fully dominant to fully recessive have been found.

174. Chromosomal aberrations can be divided into those involving changes in the normal number of chromosomes (numerical aberrations) and those involving changes in the structure of the chromosomes themselves (structural aberrations). Numerical aberrations involving loss or gain of whole chromosomes have severe clinical consequences, such as Turner's syndrome, in which the female individual has only one X chromosome instead of the normal two, or Down's syndrome, in which the individual has one extra chromosome 21. When chromosomes are broken and rejoined into new configurations which may lead to loss or gain of parts of chromosomes (deletions or duplications) the individuals receiving these may also be abnormal.

175. The Committee reviewed all data that have become available since the publication of its 1977 report and classified the new data in four groups, as follows:

(a) Those that confirm and further document previous conclusions;
(b) Those that extend the data base on which certain assumptions for risk evaluations were made in the past;
(c) Those that may be relevant for certain qualitative inferences, but not for quantitative assessments;
(d) Those which may be regarded as potentially useful to improve our evaluations of the genetic hazard posed by exposure to ionizing radiation.

176. Confirmatory data have come from studies on experimental animals. These data have extended our previous knowledge to a wider range of radiation doses and irradiation conditions (internal and external irradiation, various dose rates), to several mammalian species, many germ cell stages and genetic end-points. On the whole, these new results have strengthened our understanding of the form of the dose-response relationships in the germ cells of male and female animals, on which estimates of induction of genetic defects by radiation must be based. They have also provided more confidence in the necessary inferences from animal data to the evaluation of genetic effects in humans.

177. In humans, new data have provided a firmer basis to our estimates of the spontaneous incidence of various genetic defects; however, information on radiation-induced changes in the progeny of irradiated parents continues to be limited. Technical advances may allow direct estimates of some types of damage in the genetic material of irradiated persons. The probable genetic basis of certain somatic defects has continued to remain an area of intensive research; the results show that a number of genetic diseases in humans is associated with increased radiosensitivity and with familial proneness to neoplasia.

[13] This subject is reviewed extensively in Annex I "Genetic effects of radiation".

178. Further data have become available concerning some assumptions used in risk evaluations. Thus, for instance, new results with bacteria and the fruitfly are consistent with one of the basic assumptions involved in the indirect method of risk evaluation, namely, that there is proportionality between the rates of spontaneous and of induced mutations of particular genes. New data have also confirmed that, for irradiation conditions applicable to humans, the female germ cells are mutationally less sensitive than are male germ cells.

179. Advances have also been reported which may have a bearing on genetic risk estimates in humans, at least in a qualitative sense. These pertain to findings of increased frequencies of chromosomal aberrations in somatic cells of:

(a) Population groups living under conditions of high natural background irradiation;
(b) Groups occupationally exposed;
(c) The survivors of the A-bombs in Hiroshima and Nagasaki.

Other data concern the possible clinical significance of spontaneous chromosomal abnormalities (balanced translocations, for example), a topic to which previously little attention has been paid. Finally, detailed cytogenetic studies of the chromosomal evolution in primates point to the potential use of evolutionary similarities for making inferences on the nature and effects of certain chromosomal changes inducible by radiation or other toxic environmental agents. The problem of the contribution of recessive mutations, both spontaneous and induced, to the human genetic burden has been, and continues to be, one to which it is difficult at present to provide reliable quantitative answers.

180. Although genetic risk estimates are expressed as a certain number of cases of serious genetic defects per unit radiation dose to the population, this way of expressing risk does not adequately reflect the degree of detriment or the impact of these diseases on the affected individual, his family, the health-care facilities and society in general. In this report a preliminary attempt is made to derive an index of harm for spontaneously-occurring and radiation-induced genetic diseases. To this end the Committee used certain measurable criteria such as the length of life lost or impaired. Although recognizing that the above criteria are still inadequate, the Committee regards the attempt as one possible way to refine risk in socially meaningful terms.

181. The main objective of the Committee's review has been the assessment of possible genetic risks of radiation in humans. Direct human data, particularly at low doses and dose rates, are, however, still very limited and the assessments must of necessity continue to be based on data obtained in the mouse and, to some extent, in the non-human primates. In using such experimental data to estimate the expected effects in humans a number of assumptions are required. The most important are that

(a) Unless there is evidence to the contrary, the amount of genetic damage induced by a given type of radiation under a given set of conditions is the same in the germ cells of the test species and in those of humans;
(b) Physical and biological factors affect the magnitude of damage in similar ways and to similar extents in humans as in the test species.

The Committee stresses again the uncertainties and limitations of the extrapolation procedure and its assumptions.

182. As on previous occasions, two methods were used to obtain genetic risk estimates. With the direct method the amount of a given type (or types) of genetic damage is estimated for the test species. This estimate, with suitable correction factors, is then expressed in terms of effects expected in the progeny of exposed human individuals. With the indirect, or doubling dose method, an assessment is first made of the amount of radiation that will produce as many mutations as occurring spontaneously in the test species. An average of the estimates for the different categories of damage is the "doubling dose" for the species in question. Under the assumption that the doubling dose so estimated is applicable to man, and taking into account the current incidence of genetic diseases in humans, the expected increase of diseases per unit radiation dose is finally calculated.

183. Using the direct method, the Committee estimated in 1977 that the risk of induction of mutational damage in the first generation following irradiation of males (low dose, low dose rate, low-LET radiation) would be of the order of 2000 cases of serious genetic disorders per Gy per million progeny. The basis for this calculation had come from studies on the production of dominant skeletal mutations in male mice. No new data on skeletal mutations have been obtained that might warrant a change in this estimate. The Committee has now made another independent estimate based on the induction of dominant mutations causing cataract of the eye following irradiation of male mice. The new estimate of 1000 cases per million per Gy of paternal exposure is in reasonable agreement with that of 2000 per million per Gy based on skeletal mutations.

184. The agreement between the figures lends support to the view that the estimates are probably of the right order of magnitude. It should, however, be stressed that such estimates, however close, rest on a number of assumptions and might be subject to revisions with further advancement of scientific knowledge. Estimates of risk to the offspring of irradiated females cannot be obtained by the same approach, owing to the lack of relevant experimental data. Inferences from other data, however, point to a lower, and probably to a much lower, sensitivity of the female germ cells, as compared with those of the males for low dose, low dose rate, low-LET irradiation conditions.

185. The Committee has also been able to reassess risk from induction of reciprocal translocations, on the basis of new data from studies with the rhesus monkey, as well as of previous data on marmosets and men. This risk is now estimated to lie between about 30 and about 1000 cases of congenitally malformed children per million conceptions per Gy of paternal irradiation (low dose, low dose rate, low-LET irradiation). These cases would derive from the unbalanced products of radiation-induced balanced reciprocal translocations. However, in the absence of sufficient data on the effect of such translocations on the carriers themselves, the contribution of balanced reciprocal translocations as such to human ill-health cannot be reliably assessed. As to the risk from the induction of reciprocal translocations in females, no new data have appeared. Again, inferences from data support the Committee's view, expressed in the 1977 report, that the risk is likely to be low. The same conclusion would apply to structural

aberrations of chromosomes, other than those specifically mentioned above.

186. Using the indirect, or doubling dose method, the Committee estimated in 1977 that when the population is continuously exposed to low doses of low-LET radiation at the rate of 0.01 Gy per generation (1 generation = 30 years), 63 new cases of genetic diseases per million first generation progeny would be expected (20 from the induction of dominant and X-linked ones, 38 from chromosomal ones, 5 with complex aetiology). At equilibrium (which would be reached after different numbers of generations, depending on the category of genetic disease) this number would increase to 185 cases per million progeny (100 from the induction of dominant and X-linked diseases, 40 from chromosomal ones, and 45 from those with a complex aetiology).

187. Recent analyses have permitted some refinement of these estimates. Firstly, it has been shown that, for dominant and X-linked diseases, the first-generation increment is likely to be about 15% of that at equilibrium (i.e., for low-LET, low dose radiation exposures at the rate of 0.01 Gy per generation, 15 cases per million births, the equilibrium frequency being the same as before, namely, 100 cases per million births; or, for an exposure at the rate of 1 Gy per generation, 1500 cases per million births in the first generation and 10 000 cases per million births at equilibrium). Secondly, most of the diseases included under the category of chromosome anomalies are numerical ones. In 1977, the increment (due to radiation under the stated conditions) for this class of diseases was estimated on the assumption of a doubling dose of 1 Gy, as for other categories of genetic damage. However, data on experimental animals and man point to the possibility that a doubling dose of 1 Gy may be inappropriate for numerical chromosomal diseases. The Committee has therefore used the above doubling dose only for those chromosomal diseases stemming from structural aberrations of chromosomes and has arrived at estimates of 240 and 400 cases per million progeny in the first generation and at equilibrium, respectively, when the population is exposed to 1 Gy per generation under the stated conditions. There has been no change in the estimates with respect to diseases of complex aetiology (i.e., the figures of 450 and of 4500 per million progeny in the first generation and at equilibrium, respectively, remain valid for a radiation exposure of 1 Gy per generation under the stated conditions).

188. In summary, using the doubling dose method, the Committee now estimates that, when a population is exposed to low-LET irradiation at low doses at a rate of 1 Gy per generation, the expected increase in the incidence of genetic diseases will be about 2200 cases per million progeny in the first generation (i.e., 1500 + 240 + 450 ≈ 2200) and of about 15 000 cases per million progeny at equilibrium (i.e., 10 000 + 400 + 4500 ≈ 15 000).

2. Non-stochastic effects of irradiation on normal tissues[14]

189. When radiation kills a sufficiently large number of cells, it causes anatomical and functional tissue damage. Doses below a given threshold, which is variable for various effects and tissues, may produce detectable changes but relatively higher doses are generally required to induce pathological effects. For single whole-body doses in excess of the threshold, bone marrow is the critical tissue for survival. However, the large capacity for repopulation of the marrow enables it to withstand much larger doses if administered over a long time. With protracted or fractionated irradiation the loss of function of other tissues (for example, the testis or the lens of the eye) may appear at lower doses. The review of the Committee examines, for all important tissues, the dose-time relationships under which the various effects become critical. It also discusses the relative importance of other physical or biological variables.

190. No systematic analysis of the morphological and functional changes in irradiated normal tissues had been undertaken by the Committee since 1962. The objectives of the present review were firstly to identify for each tissue and for various modalities of irradiation, the effects and the doses that may become critical for the function of that tissue; and, secondly, to analyse the main physical and biological factors which modify these doses and effects. These objectives required a complex study of the dose-time relationships in each tissue, based both on animal data and on clinical effects in man.

191. The study was confined to non-stochastic effects. These effects arise when a large proportion of cells in a tissue are inactivated by radiation, thus giving rise to anatomical or functional tissue damage. In general, non-stochastic effects require that a minimum dose, called the threshold dose, be delivered before they can be detected. The clinical severity of the injury increases with increasing dose. The time of appearance of tissue damage is very variable, ranging from a few hours or days to many years after exposure, depending on the type of effect and on the characteristics of the particular tissue.

192. The concept of dose threshold is difficult to define and must be discussed in relation to each tissue and effect because it depends to a large extent on the sensitivity of detection. There is also a need to distinguish between the threshold of detection of any effect, however small or trivial, and the threshold of appearance of clinical changes with clear pathological connotations. While recognizing that these concepts have important practical implications, the Committee felt that a thorough discussion of tissue pathology was beyond the scope of this study, which was primarily aimed at an assessment of the effects as reported, rather than their significance for practical purposes.

193. The information available on these subjects is very large and an interpretative, rather than a comprehensive, treatment was therefore necessary. This was facilitated by the significant advance in knowledge of the basic mechanisms of cell and tissue response to irradiation. The premise of the Committee's review is that the non-stochastic response of a given tissue to radiation depends primarily on the level of killing of the component cells and that the degree and timing of damage are related to the special way in which each given tissue is organized and functions. Therefore some discussion of basic radiobiological concepts was first required, to outline the effects of radiation on cells and tissues, the repair phenomena, the functional structure of tissues and the changes induced by radiation therein. All this was intended as a unifying frame of reference for the specialized and systematic analysis of effects in various tissues.

[14] This subject is reviewed extensively in Annex J "Non-stochastic effects of irradiation".

194. Although the Committee has considered human data separately from other animal data, for the purpose of the present report the similarities between the observed effects warrant a common treatment of the subject matter, with the necessary qualifications to point out discrepancies. Doses quoted in this subsection are absorbed doses in gray (Gy) from x or gamma rays administered in conventional fractionated radiotherapy, unless otherwise specified.

195. In skin radiation reactions range from a temporary reddening and loss of hair, to atrophy, permanent epilation, colour changes, anatomical changes of the blood vessels, ulceration and necrosis. In order to produce observable changes in animal skin by external x or gamma irradiation, acute doses of the order of 7 to 10 Gy must normally be administered. However, as this tissue has a very large capacity for repair, up to 5 times more dose may be tolerated when radiation is delivered over weeks or months. Observations on patients following radiotherapy generally confirm these findings. With single treatments temporary loss of hair is seen after 3 to 5 Gy and mild reversible skin changes normally occur after 1 or 2 Gy. However, human skin may receive up to 50 or 60 Gy spread out during 6 weeks, without severe consequences developing. The area and depth of skin irradiated is important, with more severe changes appearing for irradiation of larger areas and deeper layers. Other biological variables are also known to influence the level of the threshold dose: among these are the anatomical location of the skin, the age of the irradiated person, and the normal skin colour. Mucous membranes exhibit changes analogous to those seen in the skin at similar doses.

196. In experimental animals, blood-forming tissues are particularly sensitive. Lymphocytes and stem cells are largely inactivated by single doses of a fraction of a Gy. These tissues have, however, a remarkable capacity for regeneration. In man the haemopoietic system is also one of the most sensitive tissues. Responses may be observed after 0.5 to 1 Gy, whether given in a single exposure or as a series of small fractions. With this tissue, as with many others, the volume irradiated is very important in determining the level of response. If depression of the peripheral blood cells is too severe, infection or haemorrhage may occur. These are the major symptoms of the so-called haematopoietic syndrome, which may lead to death.

197. External irradiation of the gastro-intestinal system results in a variety of symptoms and lesions ranging from dyspepsia and diarrhoea with loss of fluid and blood, to localized ulcers and, later, to bowel strictures and obstructions. The various sections of the gastro-intestinal tract must be treated separately since they are not uniformly sensitive. Considering the early forms of radiation injury, the stomach in man may tolerate up to 40 Gy of long-term fractionated treatment. The small intestine may also withstand doses of the order of 30 to 40 Gy over a few weeks. The large intestine is even more resistant and shows only transient symptoms at similar doses, while the oesophagus appears to tolerate fractionated irradiation up to 60 Gy. The late consequences of these large doses (particularly those given to large volumes) are little known and difficult to quantify. The liver is a relatively radioresistant organ. In animals, single doses of over 10 Gy are necessary to induce permanent changes in liver and these doses may be increased up to six times upon extended fractionation. In man, the liver is known to tolerate 40 to 50 Gy in 30 days given to parts of the organ, the threshold for measurable effects being around 30 Gy of conventional fractionated radiotherapy.

198. Moderate doses of radiation to the lungs may result in pneumonitis which leads eventually, through a complex chain of pathological reactions, to fibrosis and loss of function. The sensitivity of the lung with respect to long courses of irradiation is moderate. Doses of over 20 Gy given in a few weeks may lead to an appreciably increased incidence of complications. Among other thoracic organs, the heart is regarded as being rather radioresistant in experimental animals where it shows only microscopic changes in the muscle cells and blood vessels after moderate doses. In man, a high incidence of cardiac complications, consisting mainly of pericarditis and eventually fibrosis, is seen after long fractionation courses to total doses in excess of 60 Gy.

199. There is a wide range of sensitivities among the various structures of the urinary system: the kidney is believed to be the most vulnerable, followed by the bladder and the ureters. Acute and chronic nephritis followed by hypertension and proteinuria usually result from high radiation doses to the kidney. In experimental animals, changes have been reported after acute irradiation with threshold doses between 5 and 12 Gy. With conventional fractionation these doses might be increased by a factor of at least 3. In man, a dose of 20 to 24 Gy in 3–4 weeks results in alterations in kidney function, so that the tolerance dose in radiotherapy is normally regarded to be around 23 Gy in five weeks. In both humans and experimental animals the kidney appears to be more sensitive at around the time of birth. The tolerance dose to the urinary bladder is taken to be 55 to 60 Gy delivered over 3–4 weeks.

200. The testis and ovary are particularly sensitive. Irradiation of the testis may cause either temporary or complete sterility, depending on the dose. The testis appears to be unique, in that fractionated irradiation causes more, rather than less, non-stochastic damage than single treatments. In man, single doses as low as 0.1 Gy have been reported to cause temporary sterility, although doses in excess of 2 Gy are needed to produce permanent aspermia. Many years may sometimes be necessary for complete functional recovery after severely damaging doses. The adult ovary is more resistant than the testis, because, by the time of birth, the oogonial cells have all progressed to the more resistant oocytes. However, if irradiation is delivered to the developing ovary, fractionated treatments to a total of 2 Gy cause severe damage in dogs and monkeys. Permanent sterility is caused in women by single doses in excess of about 3 Gy, or higher fractionated doses.

201. The threshold doses for the central nervous system differ for different structures. The lesions consist in alterations of the glial structure, loss of myelin, encephalitis and necrosis. The more severe damage is believed to result, at least in part, from primary lesions of the blood vessels, and it is irreversible. The central nervous system has limited capacity for regeneration. Data in animals show that structural damage to the glial cells may occur after doses of 1 to 6 Gy, which may produce cellular degeneration some months after treatment. Higher doses will cause earlier effects. In man the radiotherapy tolerance dose for the whole brain is around 55 Gy delivered in 5 to 6 weeks, but morphological changes are seen after 10 Gy of fractionated treatment. Threshold doses for the spinal

cord are lower, in the region of 35 Gy in 4 weeks. Fractionation effects are particularly important for brain and cord.

202. Irradiation of growing cartilage leads to disturbances in the process of bone formation, with resulting deformities. Growing cartilage is very sensitive and the threshold dose to cause growth stunting is probably small and possibly zero. In the young animal, about 3% stunting per Gy has been reported. In children, total doses of 10 Gy or more given in daily fractions over a few weeks are sufficient to cause some degree of reduced growth. The younger the child, the more severe the degree of stunting. Mature cartilage, on the other hand, may tolerate much higher doses. In general, adult bone is considered to be fairly resistant and total doses of 65 Gy given in 6–8 weeks do not normally cause necrosis: there may be however predisposition to fracture, depending on the mechanical stress normally exerted on the bone.

203. Of the many tissues in the region of the eye (lacrimal glands, conjunctiva, cornea, sclera, retina) the lens is the most sensitive to radiation, with production of lens opacifications or clinical cataract. Initial effects are seen in man after 2 Gy of acute exposure. In some animals such as the mouse, much lower doses are usually required to cause early cataract. For the lens the increase in threshold dose with increasing fractionation may be rather less than for many other tissues. Regarding the endocrine organs, in the adult the pituitary is regarded as radioresistant. The thyroid is a slowly proliferating tissue in which radiation effects may become apparent after many years. Doses of the order of 10 Gy in a single treatment are necessary to cause morphological damage to thyroid cells and evidence of malfunction.

204. The time sequence between changes in the blood vessels and in parenchymal tissues suggests that vascular injury may play an important role in pathological changes (cell loss, fibrosis) following high doses of radiation, although it is difficult to assess the reaction of vascular and parenchymal components separately. Morphological damage is known to occur in the blood vessels of irradiated organs, and long after exposure these changes may lead to disturbances of vascular function. Threshold doses for relatively subtle changes tend to be lower than for more marked functional injuries. Blood vessels located in different tissues may have different thresholds of reaction.

205. The Committee reviewed systematically the effects produced by fast neutrons that are known to produce, dose for dose, a higher degree of biological effects than x or gamma rays. For acute doses causing detectable injury, the effectiveness of neutrons is normally between 1 and 5 times that of x or gamma rays. Neutrons are even more effective in the course of fractionated treatments as the dose per fraction decreases.

206. The non-stochastic effects produced by beta- or gamma-emitting radionuclides administered internally are usually consistent in type and degree with those caused by comparable mean tissue doses of external irradiation given at low dose rate. The tissues affected by treatment with a given nuclide depend on the particular distribution of that nuclide in the body; the amount of injury depends on the radiation characteristics and on the temporal distribution of the energy delivered. Models to relate the temporal distribution of absorbed doses from a radionuclide to that of fractionated external irradiation on the basis of equal effects have not yet been fully explored. There are also uncertainties concerning the microdistribution of the radionuclide energy in the cellular targets, and they affect the assignment of precise values of relative biological effectiveness (RBE) to non-penetrating radiations, such as alpha particles and low-energy Auger electrons emitted by the radionuclides.

3. Radiation-induced life shortening[15]

207. Although shortening of life span is a real consequence of irradiation, a very large body of evidence in experimental animals indicates that this effect is essentially due, at low to intermediate doses and dose rates, to the induction of specific neoplastic diseases. The epidemiological data collected on the survivors of Hiroshima and Nagasaki point to the same conclusion in man.

208. Since the 1958 and 1962 reports, the Committee had not reviewed systematically the data on the non-specific effect of shortening of life that has often been claimed to occur over and above more specific (essentially carcinogenic) consequences of irradiation. The main objectives of the present Committee's review of the subject were: to examine the existence of such an effect and its relationship to natural or, possibly, radiation-induced aging; to investigate the range of doses, dose rates and irradiation conditions at which it may become apparent; to determine the influence of other biological variables (genetic constitution, age, sex) on such an effect.

209. It has repeatedly been noted in the past that animals surviving the short-term effects of irradiation showed symptoms typical of senescence (greying of the fur, appearance of cataract, loss of reproductive capacity). These animals tended to die sooner than non-irradiated controls, with an apparent shift to earlier times of diseases characteristic of late ages. Taken together, without any deep knowledge of the biology of senescence or of the radiation-induced changes themselves, these observations led to the conclusion that radiation, in addition to shortening life span, could also lead to accelerated aging. Much research was carried out in the past in an effort to substantiate this notion.

210. The Committee briefly reviewed the theories of physiological aging and the possible mechanisms that might underlie senescence. It appears that too little is known at present about the biological phenomena themselves to warrant any more extended discussion of their possible modifications by radiation. It is thought, on the contrary, that the actuarial aspects of senescence, that is the life shortening itself, could be profitably explored in respect to irradiation. In this context it is also legitimate to ask whether radiation-induced life shortening could be attributed to specific conditions or diseases or whether, and to what an extent, it may be sustained by non-specific diffuse causes.

211. There is usually little difficulty in establishing precisely the time of death and in analysing the derived statistics (mean and median survival times, age-specific mortality rates, etc.). These are, however, the end-points

[15] This subject is reviewed extensively in Annex K "Radiation-induced life shortening".

of a multiplicity of underlying phenomena. Any meaningful answer to the problems outlined in the preceding paragraph requires the ascertainment of the causes of death by careful pathological investigations, an objective which is in itself difficult, particularly in old subjects, owing to the presence of multiple and interacting diseases. Yet, such data are crucial for assessing whether irradiation has such a specific action. In principle, the Committee believes that unless it can be shown that radiation advances the time of death without modifying the spectrum and the relative incidence of diseases normally occurring in a non-irradiated population, the notion of non-specificity of life shortening is untenable. In practice, the Committee notes that a convincing experimental demonstration of non-specific life shortening has never been produced, particularly in the light of refined statistical analyses accounting for the effects of age-specific and competing diseases.

212. On the contrary, the vast majority of the data obtained in experimental animals, at doses and dose rates where short-term radiation damage is not detectable, lend no support to the views that radiation may cause premature or accelerated aging or that the induction of extra cancers, which may become evident under these conditions, is only one aspect of a more general effect of hastening the onset of aging. This is not in conflict with other observations that, at doses or dose rates high enough to cause short-term death of a sizeable fraction of the irradiated animals, non-specific damage to the blood vessels, to the connective tissues, or non-stochastic effects to other tissues, might be responsible for more diffuse non-cancerous modes of death that become apparent. Exposure to such high doses would be of relevance only under exceptional circumstances.

213. The Committee analysed the information on life shortening caused in many species and strains of experimental animals by x and gamma rays or by fast neutrons given in single doses. Single-dose irradiation is uncommon in practice but it is useful to establish an upper boundary to the effect. Although in each given experimental series the life shortening induced by the x or gamma rays follows different linear or curvilinear relationships with dose, a linear or linear-quadratic non-threshold relationship was shown to have a good fit to the pooled data from many available series in the mouse. For a linear relationship, the average life-shortening effect amounts to about 5% for a dose of 1 Gy, with differences in one or the other direction depending on the strain of the animals and their biological characteristics. In the same animal species, and for single doses of fast neutrons, a convex upward relationship of life shortening to dose seems to apply; here too the variability between strains is quite pronounced.

214. The condition of irradiation which is most relevant for practical purposes is one where animals are exposed at low rate for the entire duration of their life. Dose rates many orders of magnitude higher than the normal background rate must of course be used to elicit significant effects. Under continuous irradiation the efficacy of the x- or gamma-ray doses could be up to an order of magnitude lower than that of single doses. For x and gamma rays, irradiation at low dose rate spread over the whole lifetime defines approximately a lower boundary of effectiveness in experimental work. Under life-long conditions of exposure it is very difficult to distinguish between the dose and time variables and to analyse them separately, because the former accrues as a function of the latter. Thus, depending on the life span of the animals, on their susceptibility to life shortening, and on the actual values of the exposure rate, different shapes of dose-response relationships may actually be generated over a wide range of doses, but for low doses and dose rates essentially linear shapes are normally found.

215. The Committee examined all the available data concerning the effect that changing the rate of exposure or the pattern of dose fractionation has on life shortening. It concludes that, within a large range of these variables, the change of effectiveness is modest for x or gamma rays and is doubtful for neutrons. Other data were obtained by exposing animals to a protracted treatment and by terminating this treatment some time before death, which might ensure more precise evaluations of the time-dose relationships. These data are, in reality, very difficult to interpret, probably because the animal susceptibility to life shortening changes during irradiation as a result of repair phenomena stimulated by the radiation treatment itself. In general, however, the life-shortening response following such treatments is found to be intermediate between that of the very high dose rate and that of the very extended low dose rate modalities.

216. In cases of internal irradiation by injected or ingested radionuclides conditions of selected exposure of particular organs or tissues usually apply, owing to the concentration of the various radionuclides in different parts of the body. It has been shown that under these conditions the life shortening that is seen may be explained by the induction or acceleration of cancers in the irradiated body sites, except at the very high doses where non-stochastic early damage may become detectable.

217. The effectiveness of neutrons up to 14 MeV in producing life shortening compared with the effectiveness of x or gamma rays has also been examined. In single experimental series, fairly high doses of neutrons are 3 to 10 times more effective in causing distinct life shortening. Higher RBE values apply at lower doses and dose rates.

218. The Committee reviewed the biological variables affecting life shortening. Among them, the genetic characteristics of species and strains, the sex, and the animal's age, both before and after birth, were considered. Also, the modifications of the life-shortening effect brought about by various physical, chemical or biological treatments were examined. In view of the fact that life shortening depends so much on the pathological characteristics of various species, the Committee believes that quantitative projections of data from experimental animals to man under conditions of practical significance would be unwarranted in the light of present knowledge.

219. In occupationally exposed people, radiologists in particular, radiation-induced diseases such as leukaemia and cancer of the skin occurred in the early days after x rays and radium were discovered. Some life-span reduction over and above that attributable to these conditions may have been present in pioneer radiologists exposed over a long period of time to unknown but probably high doses, as shown by some, but by no means all, data. However, life shortening not associated with cancer was reported to have disappeared in radiologists who began to be exposed after radiation protection practices came into operation. It

should logically follow that up to the range recommended as "permissible" at the times when these exposures took place (that is, at dose limits up to ten times higher than those presently accepted) no reduction of life span could be expected and any residual prevalence of leukaemia and cancer induced by radiation would be insufficient to cause a statistically detectable shortening of life in the human species, within the sample sizes usually analyzed.

220. The data obtained from groups of radiotherapy patients show no evidence of life shortening. This statement is limited by the nature of the underlying data and particularly by two considerations. Firstly, the fact that only a part of the body was irradiated in these patients and under these conditions there would be less reason to expect much unspecific shortening of life; secondly, the size of the groups examined is usually smaller than that of the occupationally-exposed individuals and very much smaller than in the cases of the A-bomb survivors.

221. The appearance of cases of leukaemia and cancer in excess of the average spontaneous rate of induction did produce some shortening of life among the survivors of the A-bomb explosions in Japan. The magnitude of such an effect can be accounted for entirely by these malignancies and a non-specific cause need not be postulated. The very large sample size on which these observations have been made, and the fact that they have been confirmed during more than thirty years, even though applying only to the oldest cohort of the population, make this conclusion reasonably sound.

4. Biological effects of radiation in combination with other agents[16]

222. The combined effects of radiation and of other physical, chemical and biological agents are potentially of great importance but the relevant data are scattered and inconsistent. Therefore the emphasis of this review has been mainly theoretical, with illustrative examples of the complexities of the subject drawn from experimental and epidemiological reports. Except for the case of tobacco smoke, which may act synergistically with radiation in producing lung cancers under some working conditions, this study has been unable to document in man any clear case of interaction, at least of the kind which may result in substantial modifications of the estimates of risk for significant sections of the population. The Committee has outlined the main directions along which future work might be usefully pursued since data on combined effects are at present inadequate.

223. The joint effects of ionizing radiation and other physical, chemical or biological agents are of potentially great importance because radiation is ubiquitous in nature and in modern life many situations could be envisaged which might lead to some form of interaction.

224. In spite of many reports claiming or showing some kind of interaction, the Committee believes that the results of these studies are, on the whole, inconclusive, for a number of reasons. First, when considered comprehensively in the light of the Committee's objectives, these reports appeared to involve exposure levels much higher than the environmental levels of practical significance, and to involve single, rather than protracted, exposures. Secondly, there was a lack of any systematic treatment of each case of interaction in regard to the dosage of the interacting agents and to the interaction mechanisms. Thirdly, many of the reports made little use of appropriate methodologies of analysis, although these had long been available in other fields of the biological sciences. Finally, the absence of sound conceptual bases about the possible nature of the interaction made it impossible to define this notion to even a moderate degree of refinement.

225. Given the above situation, the Committee assumed that a preliminary theoretical treatment of the field in an attempt to suggest definitions, to identify methodologies of analysis, and to exemplify the complex nature of the problems with practical examples, would be more appropriate than a systematic review of literature reports. The Committee considered two possible types of interactions. In the first type both ionizing radiation and the other interacting agent may each produce some effect: here, additivity, synergism and antagonism are seen as the three possible conditions of interaction. The second type is that between ionizing radiation and any other agent which is by itself inactive when administered alone: protection and sensitization are here the terms describing the reduction or the enhancement, respectively, of the effects of radiation acting alone. Such a classification is not an absolute one because the doses of the interacting agents and the types of effect may influence profoundly the nature and degree of the interaction. Cancer-promoting substances were examined as a special case.

226. The concepts of exposure, dose and response as applicable to the special case of combined actions were first discussed. The Committee then reviewed the existing methodologies of analysis, which might allow an assessment, at least qualitative, of the results of combined treatments. A more detailed probabilistic discussion of this subject was also provided leading, under certain conditions, to a precise description of the interaction factors. Attention was given to the applicability of these basic but rather abstract concepts to practical situations in the presence of complex biological effects.

227. In order to produce meaningful answers, the biological effects under study must be well defined and explored for the full range of doses of the interacting agents, applied both separately and jointly. The temporal pattern of the exposure (contemporaneous or sequential, single or fractionated) and the order of administration of the agents are often of decisive importance in respect to the production of a given type and degree of effect. A detailed knowledge of the mechanisms is also a prerequisite for the assessment of the conditions and the level of interaction. However, in much of the work examined these basic requirements were not met or were only imperfectly explored; also, the statistical significance of the results was often so low as to make any assessment of interaction at best suggestive.

228. Regarding the interaction of radiation and other physical agents, the available information was mostly on interactions between different types of ionizing radiation or between ionizing radiation, on the one hand, and ultraviolet radiation, microwaves and heat, on the other. Some synergistic action was apparently

[16] This subject is reviewed extensively in Annex L "Biological effects of radiation in combination with other physical, chemical and biological agents".

reported in workers in the radiotechnical industry exposed jointly to ionizing radiation and microwaves. Functional disturbances of the autonomic nervous system and subjective symptoms of discomfort were the effects under study. A critical analysis of the data showed that the nature of the symptoms, the difficulty with their quantification, the insufficiently controlled conditions of exposure and the incomplete statistics were all reasons to regard these reports with some reservation. Fewer data were available on the combined action of radiation with high altitude, physical stress, mechanical damage and ultrasound, and the results seemed on the whole inconclusive.

229. Many different classes of chemical compounds have been examined for their possible interaction with radiation. Inorganic compounds containing lead, cadmium, chlorine, beryllium and platinum may be of importance under special conditions of work and the very limited experience available could profitably be enlarged for more definitive conclusions. Data on various types of dust were thought to be very uncertain because additive, synergistic and inhibitory effects were described, to a degree not exceeding a factor of four under the worst possible circumstances, compared with the effects induced by radiation alone. Antibiotics, chemotherapeutic substances and other pharmacological agents appeared to be of more significance under special clinical situations than for the population at large.

230. The possible combined action of radiation with compounds known for their carcinogenic properties was the object of special attention. Although the information reviewed concerned a variety of initiators and promoters, the data available for each of these substances were very incomplete and the evidence conflicting. No final statement could be offered in regard to any substance or to any class of tumour unless the dose, the dosage schedule and the treatment modalities of the combined treatments had been analysed to a greater depth. The experience on benzo(a)pyrene, diethylnitrosamine, various types of dust and oil exhaust fumes might be enlarged for firmer conclusions, in view of the widespread environmental presence of these substances.

231. It appears that in man tobacco smoke may act by shortening the time of appearance of lung cancer induced by alpha particles of radon daughters. It is not yet clear whether such an action might result from promotion by some specific component of tobacco smoke, or might be ascribed to other non-specific effects on the respiratory tissues. The precise evaluation of the interaction factor may depend critically on the length of the observation period, as well as on the age structure and exposure history of the persons at risk.

232. In animals, there is evidence that some hormones may affect the time or rate of appearance of radiation-induced tumours, particularly of the mammary gland. This type of synergism is mainly expressed through a shortening of the time necessary for tumour induction. There is, however, a large variability of the synergistic effect with the strain of the animals, such that the same treatment schedule will produce synergism in some strains and antagonism in others. There is also variability in relation to tumour type. In man direct information is lacking. Other biological agents such as viruses and bacteria, or changes in diet, when applied in conjunction with radiation, have produced equivocal or negative results.

5. Summary and conclusions

233. The studies carried out by the Committee in the area of biological effects of ionizing radiation have not resulted in major revisions of the current thinking about the genetic risk estimates or the somatic effects analyzed. They have however focussed on some important new developments and have led to refinements of previous knowledge. On the whole, these new studies have strengthened the Committee's belief that the mechanisms of some radiation effects are becoming reasonably well understood. This applies particularly to non-stochastic effects.

234. For other effects, such as those depending on the neoplastic transformation of the irradiated cells, present knowledge of mechanisms is still largely incomplete. A further analysis of cancer induction mechanisms will be undertaken when the dosimetry in Hiroshima and Nagasaki survivors is clarified. The Committee will continue its surveillance and reviewing of the whole field of radiation carcinogenesis, including the theoretical foundations and the actual risk estimates of cancer induction in man.

235. With regard to hereditary effects, the Committee notes that further advances have been made in our knowledge of the dose-response kinetics and other aspects of some of the more important types of genetic change which can be induced by radiation in experimental mammals. Extensive use of experimental data for genetic risk assessment is still considered essential in the absence of significant positive results with respect to hereditary effects after human exposures. A new method has been developed for assessing the magnitude of first-generation risks from harmful dominant mutations. This approach and other methods for estimating genetic risks in the progeny of those exposed to low radiation doses have yielded very similar results. However, many important problems remain. For instance, human female germ-cells are considered to be less sensitive than male ones for the induction of genetic damage from low-level radiation, but the actual magnitude of this difference is still uncertain. Further work will also be needed on the extent to which recessive mutations lead to genetic damage over many generations after the first. However, advances in human genetics and new methods of comparing mutation rates in human and animal cells should help to solve some of these outstanding problems.

Appendix I

LIST OF MEMBERS OF NATIONAL DELEGATIONS

The specialist scientists who took part in the preparation of this report while attending sessions of the Committee as members of national delegations are listed below.

ARGENTINA

D. Beninson (Representative), A. J. Gonzalez (Representative)

AUSTRALIA

K. Lokan (Representative), J. R. Moroney (Representative)

BELGIUM

M. Errera (Representative), F. H. Sobels (Representative), B. T. Aten, J. Maisin

BRAZIL

E. Penna Franca (Representative)

CANADA

G. Butler (Representative), E. G. Letourneau (Representative), A. M. Marko (Representative), W. R. Bush, E. Muller, D. K. Myers, F. Prantl, H. Rothschild

CZECHOSLOVAKIA

M. Klimek (Representative)

EGYPT

M. El-Kharadly (Representative)

FRANCE

H. Jammet (Representative), A. Bouville, R. Coulon, B. Dutrillaux, J. Lafuma, P. Pellerin

GERMANY, FEDERAL REPUBLIC OF

F. E. Stieve (Representative), U. Ehling, W. Jacobi, A. Kaul, H. Kriegel, L. Rausch, C. Streffer

INDIA

V. A. Shah (Representative), S. D. Soman (Representative), K. Sundaram (Representative)

INDONESIA

A. Baiquni (Representative), O. Iskandar

JAPAN

T. Kumatori (Representative), K. Misono (Representative), R. Ichikawa, A. Kasai, Y. Kishimoto, S. Kobayashi, S. Nakai

MEXICO

J. R. Ortiz-Magana (Representative), J. R. Telich (Representative)

PERU

C. Guzman-Acevedo (Representative), M. Zaharia (Representative)

POLAND

Z. Jaworowski (Representative)

SUDAN

A. Hidayatalla (Representative)

SWEDEN

B. Lindell (Representative), K. Edvarson, K. G. Lüning, J. O. Snihs, G. Walinder

UNION OF SOVIET SOCIALIST REPUBLICS

A. Guskowa (Representative), A. M. Kuzin (Representative), R. M. Alexakhin, A. Moiseev, V. V. Redkin, V. A. Shevchenko, A. I. Vichrov

UNITED KINGDOM OF GREAT BRITAIN AND NORTHERN IRELAND

E. Pochin (Representative), C. O. Carter, K. E. Halnan, F. Morley, A. G. Searle

UNITED STATES OF AMERICA

R. D. Moseley (Representative), W. K. Sinclair (Representative), R. E. Anderson, R. Baker, A. M. Brues, C. Edington, J. H. Harley, F. A. Mettler, W. L. Russell, J. B. Storer, J. C. Villforth, H. O. Wyckoff

Appendix II

LIST OF SCIENTIFIC STAFF AND CONSULTANTS WHO HAVE CO-OPERATED WITH THE COMMITTEE IN THE PREPARATION OF THIS REPORT

D. Beninson
B. G. Bennett
A. Bouville
R. H. Clarke
M. Coppola
M. F. Cottrall
S. B. Field
B. Lindell
J. Liniecki
V. Lyscov
R. B. Persson
K. Sankaranarayanan
G. Silini
J. O. Snihs
F. D. Sowby
F. Taylor
G. A. M. Webb

Appendix III

LIST OF REPORTS RECEIVED BY THE COMMITTEE

1. Listed below are reports received by the Committee from Governments between 13 April 1977 and 26 March 1982.

2. Reports received by the Committee before 13 April 1977 were listed in earlier reports of the Committee to the General Assembly.

Document No.	*Country*	*Title*
A/AC.82/G/L.		
1561	United States of America	Health and Safety Laboratory: Environmental Quarterly, HASL-318, April 1, 1977
1562	France	Surveillance de la radioactivité en 1976
1563	United Kingdom of Great Britain and Northern Ireland	Radioactive fallout in air and rain: results to the end of 1976
1564	Germany, Federal Republic of	Environmental radioactivity and radiation levels in the year 1975
1565	United States of America	Health and Safety Laboratory: Environmental Quarterly, HASL-321, July 1, 1977
1566	United Kingdom of Great Britain and Northern Ireland	Radioactivity in human diet in the United Kingdom, 1976
1567	Japan	Radioactivity Survey Data in Japan, Number 41, November 1976
1568	Japan	Radioactivity Survey Data in Japan, Number 42, April 1977
1569	United States of America	Health and Safety Laboratory: Environmental Quarterly, HASL-328, October 1, 1977
1570	United States of America	Health and Safety Laboratory: Final tabulation of monthly strontium-90 fallout data: 1954–1976. HASL-329, October 1, 1977
1571	Switzerland	20th Report of the Federal Commission on Radioactivity for the year 1976
1572	Germany, Federal Republic of	The content of radioiodine in air, rain, grass, cowmilk and goatmilk following the Chinese nuclear test explosion on 26 September 1976
1573	United States of America	Environmental Measurements Laboratory: Environmental Quarterly, EML-334, January 1, 1978
1574	United Kingdom of Great Britain and Northern Ireland	Fallaout in rainwater and airborne dust — levels in the UK during 1976
1575	Germany, Federal Republic of	Environmental radioactivity and radiation levels in the year 1976
1576	Japan	Radioactivity Survey Data in Japan, Number 43, November 1977
1577	United Kingdom of Great Britain and Northern Ireland	Radioactive fallout in air and rain: results to the end of 1977
1578	United States of America	Environmental Measurements Laboratory: Environmental Quarterly, EML-339, April 1, 1978
1579	United States of America	Environmental Measurements Laboratory: Environmental Quarterly, EML-342, July 1, 1978
1580	United Kingdom of Great Britain and Northern Ireland	Radioactivity in human diet
1581	United States of America	Environmental Measurements Laboratory: Environmental Quarterly, EML-344, October 1, 1978
1582	United States of America	Environmental Measurements Laboratory: Index to Environmental Quarterly, EML-345

Document No.	Country	Title
1583	United States of America	Environmental Measurements Laboratory: Regional Baseline Station, Chester, NJ; EML-347
1584	United Kingdom of Great Britain and Northern Ireland	Calculation of dose rate and air ionisation from radioactive fallout deposited at Chilton, 1951 to 1977
1585	Switzerland	21st Report of the Federal Commission on Radioactivity for the year 1977
1586	Switzerland	Radiation levels and dosimetry of the persons occupationally exposed in Switzerland in 1977
1587	Germany, Federal Republic of	Environmental radioactivity and radiation levels, annual report 1975
1588	Germany, Federal Republic of	Environmental radioactivity and radiation levels, annual report 1976
1589	Germany, Federal Republic of	External radiation exposure from natural radioactivity outside and in housings, with special reference to the influence of building materials
1590	United States of America	Environmental Measurements Laboratory: Environmental Quarterly, EML-349, January 1, 1979
1591	United Kingdom of Great Britain and Northern Ireland	Fallout in rainwater and airbrone dust — levels in the UK during 1977
1592	United Kingdom of Great Britain and Northern Ireland	Radiation exposure of the UK population
1593	Japan	Radioactivity Survey Data in Japan, Number 46, September 1978
1594	Japan	Radioactivity Survey Data in Japan, Number 47, December 1978
1595	Germany, Federal Republic of	Stochastic late effects after partial body irradiation in diagnostic radiology
1596	Union of Soviet Socialist Republics	Accumulation of radiostrontium by agricultural plants from soil in different soil and climatic conditions
1597	Union of Soviet Socialist Republics	Some peculiarities of the extra-radical pollution of agricultural plants in different soil-climatic zones of the country
1598	Union of Soviet Socialist Republics	Collective dose for the USSR population as a result of the use of the sources of ionizing radiation for medical purposes
1599	Union of Soviet Socialist Republics	Late effects expressed as a yield of the mammary tumours after iodine-131 incorporation in conditions of combined action
1600	Union of Soviet Socialist Republics	The biological danger of iodine-129
1601	Union of Soviet Socialist Republics	The distribution of strontium-90 in the soils of the Azerbaijanian SSR
1602	Union of Soviet Socialist Republics	The significance of iodine radionuclides in the toxicity of nuclear fission products
1603	Union of Soviet Socialist Republics	The content of strontium-90 and caesium-137 of global origin in the food of the USSR population 1974–1975
1604	Union of Soviet Socialist Republics	Resorption and metabolism of iodine-131 after its accumulation through grass
1605	Union of Soviet Socialist Republics	The mechanism of the influence of lime and peat on the transfer of strontium-90 to the plants
1606	Union of Soviet Socialist Republics	The model of vertical migration of ^{137}Cs in soils and prognostication of the exposure
1607	Union of Soviet Socialist Republics	The content of strontium-90 in bones of the USSR population in 1974–1975
1608	Union of Soviet Socialist Republics	Regularities in the behaviours of iodine radionuclides in the environment
1609	United States of America	Environmental Measurements Laboratory: Environmental Quarterly, EML-353, April 1, 1979
1610	United States of America	Environmental Measurements Laboratory: Environmental Quarterly, EML-356, July 1, 1979
1611	Japan	Radioactivity Survey Data in Japan, Number 48, March 1979
1612	United Kingdom of Great Britain and Northern Ireland	Radioactive fallout in air and rain: results to the end of 1978

Document No.	*Country*	*Title*
1613	Argentina	^{90}Sr and ^{137}Cs from fallout in Argentina: monitoring results to the end of 1978
1614	Germany, Federal Republic of	Radiation levels in occupationally exposed persons
1615	Germany, Ferderal Republic of	Radiation exposure in the Federal Republic of Germany in 1976 due to nuclear facilities
1616	United States of America	Environmental Measurements Laboratory: Environmental Quarterly, EML-363, October 1, 1979
1617	United States of America	Environmental Measurements Laboratory: Regional Baseline Station, Chester, NJ; EML-367
1618	Union of Soviet Socialist Republics	The application of radioactive admixtures for studies of the transport of compounds injected to the stratosphere
1619	Union of Soviet Socialist Republics	The assessment of repair parameters and the effective dose after single internal contamination of the organism with radionuclides
1620	Union of Soviet Socialist Republics	The possibility to use dogs' bones to indicate the content of strontium-90 in the human skeleton
1621	Switzerland	22nd report of the Federal Commission on Radioactivity for the year 1978
1622	United States of America	Environmental Measurements Laboratory: Environmental Quarterly, EML-370, January 1, 1980
1623	Germany, Federal Republic of	Environmental radioactivity and radiation levels, annual report 1977
1624	Germany, Federal Republic of	Report of the Federal Government on environmental radioactivity and radiation levels in the year 1977
1625	Germany, Federal Republic of	Methods and results of surveillance of radionuclides released from nuclear power plants
1626	United Kingdom of Great Britain and Northern Ireland	Radioactivity in human diet
1627	United Kingdom of Great Britain and Northern Ireland	Fallout in rainwater and airborne dust—levels in the UK during 1978
1628	United States of America	Environmental Measurements Laboratory: Environmental Quarterly, EML-371, April 1, 1980
1629	Union of Soviet Socialist Republics	Photon radiation of natural radionuclides
1630	Union of Soviet Socialist Republics	Ratio of ^{210}Po to ^{210}Pb in the bones of humans and animals
1631	Union of Soviet Socialist Republics	The content of ^{90}Sr and ^{137}Cs in food products of the Estonian SSR 1966–1975
1632	United States of America	Environmental Measurements Laboratory: Environmental Quarterly, EML-374, July 1, 1980
1633	France	Surveillance de la radioactivité en 1977
1634	France	Surveillance de la radioactivité en 1978
1635	Germany, Federal Republic of	Environmental radioactivity and radiation levels in the year 1978
1636	United States of America	Environmental Measurements Laboratory: Environmental Quarterly, EML-381, October 1, 1980
1637	Japan	Radioactivity Survey Data in Japan, Number 50, September 1979
1638	Union of Soviet Socialist Republics	Genetic effects in populations after the action of ionizing radiation
1639	Japan	Radioactivity Survey Data in Japan, Number 49, June 1979
1640	Switzerland	23rd Report of the Federal Commission on Radioactivity for the year 1979
1641	United States of America	Environmental Measurements Laboratory: Regional Baseline Station, Chester, N. J.
1642	Union of Soviet Socialist Republics	Caesium-137 and strontium-90 in the biosphere of polar regions of the USSR
1643	Union of Soviet Socialist Republics	Strontium-90 in bone tissue of the USSR population for the period 1973–1978
1644	United Kingdom of Great Britain and Northern Ireland	Radioactive fallout in air and rain: results to the end of 1979

Document No.	Country	Title
1645	Belgium	Radioactivity measured at Mol 1972
1646	Belgium	Radioactivity measured at Mol 1973
1647	Belgium	Radioactivity measured at Mol 1974
1648	France	Surveillance de la radioactivité en 1979
1649	Japan	Radioactivity Survey Data in Japan, Number 51, December 1979
1650	United States of America	Environmental Measurements Laboratory: Environmental Quarterly, EML-390, May 1, 1981
1651	Germany, Federal Republic of	Environmental radioactivity and radiation levels, annual report 1978
1652	Argentina	Radiological impact of radioactive waste management
1653	Argentina	Levels of ^{137}Cs and ^{90}Sr in environmental samples in Argentina 1960–1980
1654	Argentina	Exposure of the public related to the operation of the nuclear power plant in Atucha
1655	Argentina	Doses from occupational exposure at the Comisión Nacional de Energia Atómica during 1977–1980
1656	Argentina	Determination of absorbed doses in a computerized tomography scanner
1657	Union of Soviet Socialist Republics	Questions concerning the metabolism of carbon-14
1658	United Kingdom of Great Britain and Northern Ireland	Fallout in rainwater and airborne dust—levels in the UK during 1979
1659	United Kingdom of Great Britain and Northern Ireland	Radioactive fallout in air and rain: results to the end of 1980
1660	Japan	Radioactivity Survey Data in Japan, Number 52, March 1980
1661	Japan	Radioactivity Survey Data in Japan, Number 53, June 1980
1662	Union of Soviet Socialist Republics	The formation of effective dose during chronic intake of various radionuclides in the body
1663	Union of Soviet Socialist Republics	Isotopes of the uranium and thorium series in fertilizers containing phosphorus, arable soils and agricultural plants
1664	Union of Soviet Socialist Republics	The combined effect on the body of ionizing and non-ionizing radiation and certain other factors
1665	Japan	Radioactivity Survey Data in Japan, Number 54, September 1980
1666	Japan	Radioactivity Survey Data in Japan, Number 55, December 1980
1667	Japan	Radioactivity Survey Data in Japan, Number 56, March 1981
1668	New Zealand	Environmental Radioactivity Annual Report 1980
1669	France	Surveillance de la radioactivité en 1980
1670	United States of America	Environmental Measurements Laboratory: Environmental Report, EML-395, November 1, 1981
1671	United Kingdom of Great Britain and Northern Ireland	Environmental radioactivity surveillance programme: results for the UK for 1980
1672	Switzerland	24th Report of the Federal Commission on Radioactivity for the year 1980