EFFECTS OF IONIZING RADIATION

United Nations Scientific Committee on the
Effects of Atomic Radiation

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Report to the General Assembly,
with Scientific Annexes

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NOTE

The report of the Committee without its annexes appears as Official Records of the General Assembly, Sixty-first Session, Supplement No. 46 and corrigendum (A/61/46 and Corr. 1). The report reproduced here includes the corrections of the corrigendum.

The country names used in this document are, in most cases, those that were in use at the time the data were collected or the text prepared. In other cases, however, the names have been updated, where this was possible and appropriate, to reflect political changes.

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

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I. Deliberations of the United Nations Scientific Committee on the Effects of Atomic Radiation at its fifty-fourth session

1. Since the creation of the United Nations Scientific Committee on the Effects of Atomic Radiation by the General Assembly in its resolution 913 (X) of 3 December 1955, the mandate of the Committee has been to undertake broad reviews of the sources of ionizing radiation and its effects on human health and the environment. Exposure to radiation occurs from sources such as nuclear weapon testing; natural background radiation; nuclear electricity generation; accidents such as the one at Chernobyl in 1986; occupations that entail increased exposure to man-made or naturally occurring sources; and medical screening, diagnostic and therapeutic procedures. The Committee[1] thoroughly reviews and evaluates global and regional exposures to such sources of radiation and the doses that result from them. It evaluates the evidence of radiation-induced health effects from studies of the health of survivors of the atomic bombings of Japan and of other exposed groups. It also reviews advances in understanding of the mechanisms by which radiation-induced health effects can occur. These assessments provide the scientific foundation used, inter alia, by the International Commission on Radiological Protection (ICRP) in developing its recommendations on radiation protection and by the relevant agencies within the United Nations system in formulating International Basic Safety Standards for Protection against Ionizing Radiation and for the Safety of Radiation Sources.

2. The Committee held its fifty-fourth session[2] in Vienna from 29 May to 2 June 2006. Peter Burns (Australia), Norman Gentner (Canada) and Christian Streffer (Germany) served as Chairman, Vice-Chairman and Rapporteur, respectively. The Committee reviewed advanced versions of documents that were last considered at the fifty-third session of the Scientific Committee (26–30 September 2005), as reported to the General Assembly in the Committee's report on that session.[3] The Committee had originally envisaged that those documents would be published by 2005, but the limited availability of resources had delayed their development. Nevertheless, five scientific annexes were approved for publication in the 2006 report of the Committee. The Committee also scrutinized drafts of the other outstanding documents, namely those on exposures of the public and workers to various sources of radiation; exposures from radiation accidents; exposures from medical uses of radiation; and effects of ionizing radiation on non-human biota.

3. The Committee took note that, in its resolution 60/98 of 8 December 2005, the Assembly, inter alia, reaffirmed its decision to maintain the present functions and independent role of the Committee; endorsed the intentions and plans of the Committee for its future activities of scientific review and assessment on behalf of the Assembly; emphasized the need for the Committee to hold regular sessions on an annual basis; requested the United Nations Environment Programme (UNEP) to continue to provide support for the effective conduct of the work of the Committee and for the dissemination of its findings to the Assembly, the scientific community and the public; and urged UNEP to review and strengthen the present funding of the Committee.

4. The date 14 March 2006 had marked the fiftieth anniversary of the first session of the Committee. As part of the commemoration of that event, the Government of Japan and the Chairman of the fifty-third session of the Committee, Yasuhito Sasaki, had arranged for publication of all the past reports of the Committee to be made available electronically on its website; the structure, design and content of the website was also generally overhauled. Moreover, during the fifty-fourth session of the Committee, the Mayor and Governor of the City of Vienna hosted a reception for invited dignitaries, scientists and diplomats at the Vienna Town Hall to commemorate the anniversary. On that occasion, the Director-General of the United Nations Office at Vienna delivered a message from the Secretary-General; the special guest speaker was Hans Blix; and other speakers attended from the International Atomic Energy Agency (IAEA), the World Health Organization (WHO) and UNEP. The speakers, especially Hans Blix, highlighted the importance of the Committee's scientific work over the past 50 years, recognizing its achievements and reputation for

[1] The United Nations Scientific Committee on the Effects of Atomic Radiation was established by the General Assembly at its tenth session, in 1955. Its terms of reference are set out in resolution 913 (X) of 3 December 1955. The Committee was originally composed of the following Member States: Argentina, Australia, Belgium, Brazil, Canada, Czechoslovakia, Egypt, France, India, Japan, Mexico, Sweden, Union of Soviet Socialist Republics, United Kingdom of Great Britain and Northern Ireland and United States of America. The membership of the Committee was subsequently enlarged by the Assembly in its resolution 3154 C (XXVIII) of 14 December 1973 to include the Federal Republic of Germany, Indonesia, Peru, Poland and the Sudan. By its resolution 41/62 B of 3 December 1986, the Assembly increased the membership of the Committee to a maximum of 21 members and invited China to become a member.

[2] The fifty-fourth session was also attended by observers from the United Nations Environment Programme (UNEP), the International Atomic Energy Agency (IAEA), the International Commission on Radiological Protection (ICRP), and the International Commission on Radiation Units and Measurements (ICRU).

[3] *Official Records of the General Assembly, Sixtieth Session, Supplement No. 46* (A/60/46).

scientific independence and credibility. He reflected that, with the important developments in radiation science and major environmental challenges, there was a need to strengthen support for the Committee. The Director and Regional Representative, Regional Office for Europe, of UNEP undertook actively to explore options for enhanced future support. He considered that a more apparent relationship between the scientific appraisals made by the Committee and UNEP-led policy exchanges would facilitate joint efforts to strengthen and broaden the Committee's resource base.

5. The Committee had participated in the work of the Chernobyl Forum (which involved eight United Nations entities and the Governments of Belarus, the Russian Federation and Ukraine), whose important mission covered many aspects of the Chernobyl accident, including the review of the health effects of radiation. The Committee reiterated that the recent findings of that Forum confirmed its own essential scientific conclusions,[4] reached six years earlier, on the health and environmental consequences of radiation exposure due to the Chernobyl accident. For the general population, the main adverse health consequence that had been observed was the dramatic increase in the incidence of thyroid cancer among people who had received high thyroid doses as children in 1986. The Committee recognized that it was often difficult for the public and the media to appreciate that the radiation risks, while serious for some exposed groups, were for the general population not as significant from a radiological health point of view as they were often represented to be. Uninformed reporting of postulated numbers of projected exposure-related deaths as a result of the accident, especially reporting before and at the time of the twentieth anniversary of the accident in April 2006, had created confusion among the public. With the exception of the early deaths among emergency workers that were clinically attributable to acute radiation syndrome and the small proportion of cases of thyroid cancer (which could be attributed on epidemiological grounds to radiation exposure) that were fatal, it was not possible to attribute any specific death to late effects of exposure to radiation as a result of the accident. The Committee expressed its intention to clarify further the assessment of potential harm owing to chronic low-level exposures among large populations and also the attributability of health effects. It also recognized that some outstanding details merited further scrutiny and that its work to provide the scientific basis for a better understanding of the radiation-related health and environmental effects of the Chernobyl accident needed to continue. However, owing to its participation in the Chernobyl Forum, the Committee would now extend the work on updating its own assessments of the health and environmental consequences of the Chernobyl accident in order to scrutinize information that had become available more recently. To do so effectively, it would need to increase the participation of scientists from Belarus, the Russian Federation and Ukraine. The work could not be conducted properly without additional resources.

6. The need for restoration of an operating budget adequate to allow the Committee to fulfil its mandate from the General Assembly, expressed most recently in Assembly resolutions 60/98, 59/114 of 10 December 2004, 58/88 of 9 December 2003 and 57/115 of 11 December 2002, and in anticipation of a growing need for the Committee's expertise, was now at a critical point. The Committee reiterated its concern that reliance on a single professional in the secretariat left the Committee seriously vulnerable which in the past had hampered the efficient implementation of the approved programme of work. The Committee considered that funding in the biennium 2008–2009 had to be strengthened pursuant to resolutions 60/98, 59/114, 58/88 and 57/115. Moreover, no additional resources had as yet been provided in the biennium 2006–2007 to allow the plans endorsed by the General Assembly to be carried out effectively.[5]

7. The Committee recognized the importance of information from Member States and relevant international organizations for its work. It calls upon all Member States, specialized agencies of the United Nations system and other international and national scientific bodies, to continue to make available relevant and authorized information for its reviews, whose quality and completeness critically depend on such information.

8. The Committee decided to hold its fifty-fifth session in Vienna from 21 to 25 May 2007.

[4] See *Official Records of the General Assembly, Fifty-fifth Session, Supplement No. 46* (A/55/46).

[5] *Official Records of the General Assembly, Sixtieth Session, Supplement No. 7* (A/60/7), sect. IV, para. IV.46.

II. Scientific report

9. The Committee summarized the main conclusions of five scientific annexes for inclusion in its report for 2006, entitled "Epidemiological studies of radiation and cancer", "Epidemiological evaluation of cardiovascular disease and other non-cancer diseases following radiation exposure", "Non-targeted and delayed effects of exposure to ionizing radiation", "Effects of ionizing radiation on the immune system", and "Sources-to-effects assessment for radon in homes and workplaces". The 2006 report and its annexes should be considered taking into account the context provided by earlier substantive reports[6] of the Committee. The overall view of the Committee is that the data reviewed for its 2006 report do not necessitate changes in its current risk estimates for the cancer and the hereditary effects of radiation.

10. The present report and its scientific annexes were developed between the fiftieth and fifty-fourth sessions of the Committee, on the basis of working papers prepared by the Secretariat. Serving as Chairman, Vice-Chairman and Rapporteur respectively at those sessions were:

Fiftieth and fifty-first sessions: J. Lipzstein (Brazil), Y. Sasaki (Japan) and R. Chatterjee (Canada);

Fifty-second session: Y. Sasaki (Japan), R. Chatterjee (Canada) and P. Burns (Australia);

Fifty-third session: Y. Sasaki (Japan), P. Burns (Australia) and N. Gentner (Canada);

Fifty-fourth session: P. Burns (Australia), N. Gentner (Canada) and C. Streffer (Germany).

The names of the members of national delegations who attended the fiftieth to fifty-fourth sessions of the Committee are listed in appendix I below. The Committee wishes to acknowledge the help and advice of a small group of consultants (see appendix II below) who helped in the preparation of the material and the contributions in kind of national experts and staff of international organizations. They were responsible for the preliminary reviews and evaluations of the technical information received by the Committee or available in the open literature, on which rested the final deliberations of the Committee.

11. The sessions of the Committee held during the period under review were attended by representatives of the following United Nations specialized agencies and other organizations: WHO, IAEA and UNEP; and by the following international organizations: ICRP and the International Commission on Radiation Units and Measurements (ICRU). The Committee wishes to acknowledge their contributions to the discussions.

12. Following established practice, the present annual report of the Committee to the General Assembly does not include the scientific annexes. The full report of the Scientific Committee for 2006, including the scientific annexes, will be issued as a United Nations sales publication. This practice is intended to achieve a wider distribution of the findings for the benefit of the international scientific community. The Committee wishes to draw the attention of the Assembly to the fact that the main text of the Committee's 2006 report is presented separately from its scientific annexes in the present document simply for the sake of convenience. It should be understood that the scientific information contained in the annexes is important because it forms the basis for the conclusions of the report.

[6] For the previous substantive reports of the United Nations Scientific Committee on the Effects of Atomic Radiation to the General Assembly, see *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); ibid., *Thirty-seventh Session, Supplement No. 45* (A/37/45); ibid., *Forty-first Session, Supplement No. 16* (A/41/16); ibid., *Forty-third Session, Supplement No. 45* (A/43/45); ibid., *Forty-eighth Session, Supplement No. 46* (A/48/46); ibid., *Forty-ninth Session, Supplement No. 46* (A/49/46); ibid., *Fifty-first Session, Supplement No. 46* (A/51/46); ibid., *Fifty-fifth Session, Supplement No. 46* (A/55/46 and Corr.1 Arabic only); and *Fifty-sixth Session, Supplement No. 46* (A/56/46). These documents are referred to as the 1958, 1962, 1964, 1966, 1969, 1972, 1977, 1982, 1986, 1988, 1993, 1994, 1996, 2000 and 2001 reports, respectively. The 1972 report, with scientific annexes, was published as *Ionizing Radiation: Levels and Effects, Volume I: Levels and Volume II*: *Effects* (United Nations publication, Sales Nos. E.72.IX.17 and 18). The 1977 report, with scientific annexes, was published as *Sources and Effects of Ionizing Radiation* (United Nations publication, Sales No. E.77.IX.1). The 1982 report, with scientific annexes, was published as *Ionizing Radiation: Sources and Biological Effects* (United Nations publication, Sales No. E.82.IX.8). The 1986 report, with scientific annexes, was published as *Genetic and Somatic Effects of Ionizing Radiation* (United Nations publication, Sales No. E.86.IX.9). The 1988 report, with scientific annexes, was published as *Sources, Effects and Risks of Ionizing Radiation* (United Nations publication, Sales No. E.88.IX.7). The 1993, 1994 and 1996 reports, with scientific annexes, were published as *Sources and Effects of Ionizing Radiation* (United Nations publication, Sales Nos. E.94.IX.2, E.94.IX.11 and E.96.IX.3, respectively). The 2000 report, with scientific annexes, was published as *Sources and Effects of Ionizing Radiation, Volume I: Sources and Volume II: Effects* (United Nations publication, Sales Nos. E.00.IX.3 and 4). The 2001 report, with scientific annex, was published as *Hereditary Effects of Radiation* (United Nations publication, Sales No. E.01.IX.2).

A. Epidemiological studies of radiation and cancer

13. The Committee has always relied heavily upon results of epidemiological investigations in estimating the risks of radiation-induced cancer. Much attention has been given by the Committee to the criteria that define good-quality epidemiology studies and to the various features of such studies that must be taken into consideration for the Committee to improve its estimates. The concept of statistical power, that is the probability that an epidemiological study will detect a given level of elevated risk with a specific degree of confidence, and various factors that affect it were summarized in the Scientific Committee's 2000 report. Further elaboration of this issue in annex A of the 2006 report, entitled "Epidemiological studies of radiation and cancer", shows that the statistical power of a study is greatly affected by the sample size, the dose level(s) of the exposed group and the magnitude of the risk coefficient, such that most low dose studies reported in the literature have inadequate statistical power. Also, for low dose studies with numbers of effects that are expected to be small and which do not have any statistical power, the value of the relative risk found for any supposedly "statistically significant" results is likely to be a substantial overestimate of the "true" risk.

14. Numerous sources of uncertainty in epidemiological studies were considered, together with methods for dealing with them. A new generation of epidemiological studies has begun to provide estimates of radiation risks corrected for uncertainties in dose assessment and corrections for other uncertainties are beginning to be made. An important issue when interpreting studies that make multiple comparisons (for example, for many different types of cancer) is that the probability of obtaining a statistically significant result purely by chance increases with the number of comparisons.

15. The cancer risk estimates calculated in the Committee's 2000 report were based on data on Japanese atomic bombing survivors and used the set of survivor dose estimates produced in the mid-1980s, the so-called DS86 dosimetry. For some time, it was thought that the DS86 neutron dose estimates for the Hiroshima atomic bombing survivors were systematic underestimates, while the DS86 gamma dose estimates were thought to be more reliable. Recent analysis of the available data suggests that there are no appreciable systematic errors in the DS86 Hiroshima neutron dose estimates. The most current set of dose estimates, the so-called DS02 dosimetry, differs only slightly from the DS86 system, by amounts generally of no more than 20 per cent. Analyses using the new dosimetry indicate that estimates of cancer risk factors might fall by about 8 per cent as a result, but with no appreciable change in the shape of the dose response or in the patterns of excess risk with age or time.

16. Although the resolution of dosimetric inconsistencies in the data on Japanese atomic bombing survivors has reduced one source of uncertainty in estimating cancer risks to a population from low doses of radiation, a considerable number of other sources of uncertainty remain. A major source relates to extrapolation from the moderate dose but high dose-rate exposures received by the Japanese atomic bombing survivors to low doses and dose rates. This is also true for interpreting data on many therapeutically exposed groups. There is also uncertainty relating to the extrapolation of cancer risk to the end of lifetime. In particular, about half of the cohort of Japanese atomic bombing survivors are still alive. In estimating risk factors from the data on this cohort it is vital to determine the pattern of variation of radiation-associated cancer risk for those exposed in childhood, who are now reaching the age at which larger numbers of cancers would be expected to arise spontaneously. Another source of uncertainty relates to the transfer of radiation-induced cancer risk estimates between populations with different spontaneous cancer rates.

17. Annex A of the Committee's 2006 report reassesses the risk of incidence and the mortality of cancer from the data on Japanese atomic bombing survivors, wherever possible making use of the latest DS02 dosimetry and follow-up. It also comprehensively reviews all the evidence from studies of groups of people exposed therapeutically, diagnostically and occupationally. Annex A considers risks of cancers of the salivary gland, oesophagus, stomach, small intestine (including duodenum), colon, rectum, liver, pancreas, lung, bone and connective tissue, female breast, uterus, ovary, prostate, urinary bladder, kidney, brain and central nervous system, and thyroid; and risks of non-Hodgkin's lymphoma, Hodgkin's disease, multiple myeloma, leukaemia, cutaneous melanoma, and non-melanoma skin cancer. This somewhat extends the list of organ sites from those that had been considered in the Committee's 2000 report (cancers of the salivary gland, small intestine, rectum, pancreas, uterus, ovary and kidney, and cutaneous melanoma were not considered in that report). As with the Committee's 2000 report, annex A assesses separately the risks arising from internal and external exposure to radiation, and from so-called low-LET and high-LET (linear energy transfer) radiation.

18. There are still problems in characterizing cancer risks for some sites, owing to the low statistical precision associated with relatively small numbers of excess cases. This can limit, for example, the ability to estimate trends in risk in relation to factors such as sex, age at exposure and time since exposure. Furthermore, data are sometimes lacking or have not been published in a format that is detailed enough to allow an assessment of how risks vary among populations. An exception is breast cancer, for which a comparison of data on the Japanese atomic bombing survivors and on medically exposed women in North America points to a so-called "absolute" model for the transfer of risk estimates between populations. There are some cancer sites for which there is no evidence for an association with radiation and others where excess risks have only been seen following very high dose (radiotherapeutic) exposures. While the risk evaluations for lymphomas are affected by the small numbers of cases in several studies, these results should be contrasted with the clear relation found in many

populations between radiation and the risk of leukaemia, which is also a rare disease.

19. The increased statistical precision associated with the longer follow-up of the above studies and the resulting larger number of cancers observed has assisted in the examination of dose-response relationships, in particular for lower levels of dose. For example, the most recent data for the Japanese atomic bombing survivors are largely consistent with linear or linear-quadratic risk-dose trends over a wide range of dose levels. However, analyses restricted solely to low doses are complicated by the limitations of statistical precision, the potential for misleading findings arising from any small, undetected biases and the problem of observing statistically significant results purely by chance when performing multiple tests to establish a minimum dose at which elevated risks can be detected. Longer follow-up of large groups such as the atomic bombing survivors will provide more information on effects for low doses. However, epidemiology alone will not be able to resolve the issue of whether there are dose thresholds for radiation risks. A better understanding of biological mechanisms is necessary. In particular, the inability to detect increases in risks at very low doses using epidemiological methods does not mean that the cancer risks are not elevated.

20. New findings have also been published from analyses of fractionated or chronic low-dose exposure to low-LET radiation; in particular, a study of nuclear workers in 15 countries, studies of persons living in the vicinity of the Techa River in the Russian Federation who were exposed as a consequence of radioactive discharges from the Mayak plant, a study of persons exposed to fallout from the Semipalatinsk nuclear test site in Kazakhstan, and studies in regions with high natural background levels of radiation. Cancer risks are generally statistically compatible with, although in some studies they are somewhat higher than, those derived from the data on Japanese atomic bombing survivors. However, there are concerns about bias in all of these studies, which may explain why the cancer risk estimates are elevated in comparison with those derived from the Japanese data.

21. The results presented in annex A to the Committee's 2006 report illustrate the sensitivity of estimates of lifetime cancer risk due to radiation exposure to variations in the background rates of spontaneous cancers. These findings suggest that this variability can lead to differences that are comparable with those associated with different methods of transferring risk estimates between populations or methods of risk projection. The variability in all these projections highlights the difficulty of choosing a single value to represent the lifetime risk of radiation-induced cancer. Furthermore, uncertainties in estimates of risks for specific types of cancer are generally greater than the uncertainties in estimates of risks for all cancers together.

22. Despite these difficulties, risk estimates are of considerable value for use in characterizing the impact of radiation exposure on a population. The Committee's 2000 report emphasized, for the purpose of risk projection, models that simulated the relative risk due to radiation according to age-at-exposure or attained age. With longer follow-up studies it has become clear that these models do not fit well. The Committee's 2006 report indicates that best fits are currently obtained if the models for the risk of mortality from solid cancer simulate the relative or absolute excess risk due to radiation exposure as proportional to a product of functions involving powers of time since exposure and attained age. The current preferred leukaemia mortality models imply that the relative excess risk is proportional to a power of attained age, and absolute excess risk is proportional to a power of time since exposure. When these models are applied to any of five specific populations (China, Japan, Puerto Rico, the United States of America and the United Kingdom of Great Britain and Northern Ireland) of all ages, the lifetime risk of death from all solid cancers together following an acute dose of 1 sievert (Sv) is estimated to be about 4.3–7.2 per cent, and for leukaemia 0.6–1.0 per cent. The calculations in annex A to the 2006 report show that these values vary among different populations and with different risk models; the variation being most substantial for solid cancers. These cancer risk estimates are somewhat lower, although not by much, than those previously published in the Committee's 2000 report. Some of the reduction in cancer risk estimates may be due to the new atomic bomb dosimetry and follow-up, although a larger part is probably due to the different risk projection and transport models used, in particular for solid cancers. Lifetime cancer risk estimates for those exposed as children might be a factor of 2 to 3 times higher than the estimates for a population exposed at all ages. However, continued follow-up of existing irradiated cohorts will be important in determining lifetime risks. The results from analysing the data on the Japanese atomic bombing survivors are consistent with a linear or linear-quadratic dose-response relationship for the risk of all solid cancers together and with a linear-quadratic dose response relationship for leukaemia.

B. Epidemiological evaluation of cardiovascular disease and other non-cancer diseases following radiation exposure

23. Annex B to the Committee's 2006 report, entitled "Epidemiological evaluation of cardiovascular disease and other non-cancer diseases following radiation exposure", considers epidemiological investigations that have addressed diseases other than cancer. A statistically significant association between radiation dose and mortality from diseases other than cancer was first reported in 1992 from the analysis of the Life Span Study of the data on the Japanese atomic bombing survivors for the period 1950–1985. Significant associations were seen for cardiovascular disease and other non-cancer diseases. The excess mortality from those diseases could not be explained by the effects

of smoking or other possible factors and thus the possibility that radiation was the direct cause of those effects needed to be considered. Annex B concentrates primarily on the findings from that Life Span Study and others that relate to cardiovascular diseases.

24. Effects of exposure to radiation on conditions other than cancer were most recently reviewed in the Committee's 1982 and 1993 reports, showing the presence of a minimum dose—a threshold dose—below which no radiation effects are detected clinically. Although a value for the threshold dose is difficult to define and may vary according to tissues and measuring techniques, the atomic bombing survivor data show that associations between radiation exposure and the incidence of diseases other than cancer can occur at levels of dose below those hitherto considered as thresholds for various so-called deterministic effects.

25. Annex B to the Committee's 2006 report reviews current epidemiological data and attempts to characterize the nature of the risk of non-cancer disease associated with exposure to radiation. It discusses several methodological issues that are especially relevant for assessing epidemiological data for non-cancer diseases. It then provides a general overview of currently available data on major diseases other than cancer from some 50 irradiated populations. Epidemiological data have been reviewed in detail for cardiovascular disease, which is one of the most common diseases and the one for which relatively more information on possible causation by radiation exposure is currently available. Annex B also identifies important gaps in knowledge regarding the nature of this risk and discusses the possible impact on future radiation risk assessment.

26. There is an increased risk of cardiovascular disease associated with high radiation doses to the heart, which may be incurred during radiotherapy, although newer treatment techniques resulting in lower cardiac doses have reduced the risk substantially. To date, the evidence for an association between fatal cardiovascular disease and radiation exposure at doses in the range of less than about 1–2 gray (Gy) comes only from the analysis of the data on the Japanese atomic bombing survivors. Other studies provide no clear or consistent evidence of a risk of cardiovascular diseases for radiation doses of less than about 1–2 Gy. The Committee judges that, overall, the data are not sufficient to determine appropriate risk models for these end points. The scientific data are also not at present sufficient to conclude that there is a causal relationship between exposure to ionizing radiation and the incidence of cardiovascular disease for doses of less than about 1–2 Gy.

27. Because of the high occurrence of cardiovascular disease in non-exposed populations, and its multifactorial nature and heterogeneity, as well as the need to account for major confounding factors (such as tobacco use, genetics and cholesterol level), it is uncertain whether epidemiological studies alone will be able to add significantly to the understanding of the potential for and nature of any possible causal relationship between the incidence of cardiovascular disease and radiation exposure.

28. For mortality from the group of all diseases apart from cardiovascular disease and cancer, the evidence for an association with radiation exposure at doses of less than about 1–2 Gy is also only derived from the analysis of the atomic bombing survivor data. Scientific evidence from other studies for inferring a causal relationship with radiation exposure for doses of less than about 1–2 Gy is even less sufficient than that for cardiovascular disease in these populations. This is in part because of limited data, the large heterogeneity of diseases and the various pathological mechanisms and aetiologies, as well as a multitude of confounding factors.

C. Non-targeted and delayed effects of exposure to ionizing radiation

29. The risks of cancer after high and moderate doses of radiation are relatively well understood from detailed epidemiological studies of the Japanese atomic bombing survivors and others. However, risks at the lower doses more typical of environmental and occupational exposures are generally extrapolated from the high dose data by incorporating factors to account for low dose and low dose rates. The estimation of the human health risks associated with radiation exposures are based mechanistically on the view that the detrimental effects of irradiation have their origin in irradiated cells or, in the case of heritable effects, in cells directly descended from them. However, a number of so-called non-targeted and delayed effects of radiation exposure have been described that may challenge this view. Annex C to the Committee's 2006 report, entitled "Non-targeted and delayed effects of exposure to ionizing radiation", reviews the evidence for such effects and reflects on how they may influence the mechanistic judgements required for the estimation of risk at low doses and dose rates.

30. The effects considered include radiation-induced genomic instability, bystander effects, abscopal effects, induced clastogenic factors and hereditary effects, as follows:

(a) If a single cell is irradiated and survives, it may produce daughter cells that over generations have increasing numbers of alterations in their genomes, even though the daughter cells themselves were not irradiated. This effect is termed "induced genomic instability". The alterations in the genomes of the daughter cells can include alterations in their chromosomes, changes in the numbers of their chromosomes, mutation of their genes and other deozyribonucleic acid (DNA) sequences and a reduction in the number of subsequent cells generated through daughter cell replication;

(b) The so-called "bystander" effect is the ability of irradiated cells to convey manifestations of damage to neighbouring cells not directly irradiated;

(c) An abscopal effect is said to occur if there is a significant response in a tissue that is physically separate from the region of the body exposed to radiation;

(d) There is a large body of evidence that blood plasma from irradiated animals and humans can contain so-called "clastogenic factors" capable of inducing chromosomal damage in unexposed cells;

(e) Heritable effects are those effects observed in offspring born after one or both parents has or have been irradiated prior to conception. Transgenerational effects are those that are expressed beyond the first generation;

(f) Finally, some of the manifestations of non-targeted and delayed effects noted above can arise spontaneously and after exposure to other agents.

31. In spite of the large body of new information, there continues to be considerable debate regarding the causal relationship between these non-targeted effects and the observed health effects attributable to radiation. The Committee concludes that at present the available data provide some support for concluding that there are disease associations, but not for causation. In arriving at this conclusion, the Committee stresses that the estimation of the health effects of radiation is based on epidemiological and experimental observations where there is a statistically significant dose-related increase in disease incidence. These direct observations of adverse health outcomes implicitly take account of mechanistic elements relating not only to the targeted (direct) effects of irradiation but also to the non-targeted and delayed effects described in annex C to the 2006 report.

32. The Committee continues to hold the view that mechanistic information is important for its judgements on radiation-induced health effects at doses below about 0.2 Gy. However, to ascribe a mechanism for the development of a particular health-related biological effect, the data in question need to be independently replicated and to show strong coherence with the particular disease considered. In this respect, the data on microdosimetric energy distribution in the cell nucleus and the subsequent cellular processing of directly induced DNA damage, reviewed in the Committee's 2000 report, are considered to provide a suitable foundation for judgements on mechanisms that affect risk estimation. However, the Committee recognizes that a variety of mechanistic processes will contribute to the development of radiation-induced health effects.

33. The Committee will maintain surveillance of scientific developments in the area of non-targeted and delayed effects and recommends generally that future research pay particular attention to designing studies that emphasize reproducibility, low dose responses and causal associations with health effects. Ultimately, understanding the range and nature of cellular and tissue responses to radiation will provide insights into the mechanisms by which radiation exposure induces detrimental health effects, thereby improving the scientific basis for the quantitative estimation of the risk of health effects for low doses and low dose-rates.

D. Effects of ionizing radiation on the immune system

34. The effects of ionizing radiation on the immune system were first reviewed in detail in the Committee's 1972 report and then briefly described in the 1977, 1982, 1986, 1988, 1994 and 2000 reports. Concepts in immunology have developed and changed considerably in the last three decades and so the Committee had proposed that a completely new review of the effects of ionizing radiation on the immune system was necessary. Thus, annex D to the 2006 report, entitled "Effects of ionizing radiation on the immune system", reviews data related to radiation-induced alterations of immune responses, considers the possible mechanisms involved and reviews epidemiological studies of the effects of ionizing radiation on the human immune system.

35. The immune system, one of the most complex systems of the human body, is composed of cells of several types (lymphocytes and accessory cells) strategically spread throughout the body, perfectly positioned to recognize antigens (non-self or foreign substances and cells) and to neutralize or destroy them; this protects against infections and cancer. There are two different but interrelated forms of immunity: innate and acquired immunity. Innate immunity is fully functional before any foreign agent enters the body and thereby provides a rapid defence. Acquired immunity develops after a pathogen has entered the body and maintains memory of previous exposures, yielding a stronger response following subsequent exposure to the same antigen. Acquired immune responses are mainly executed by B-lymphocytes (humoral responses) and T-lymphocytes (cell-mediated responses).

36. The effects of ionizing radiation on the immune system can be assessed by estimating changes in cell numbers or by using a variety of functional assays. The impact of such alterations in immune response depends on factors such as dose of radiation, its temporal relation to immunization and genetic disposition. Thus:

(a) High doses of radiation produce immunosuppression mainly due to the destruction of cells. Lymphocytes are very radiosensitive and their reduction is currently used as an early indicator of the level of an accidental acute exposure. Radiation-induced changes in immune parameters seem to be more dependent on total dose than on dose rate. Persisting effects on the immune system have been observed after exposure to ionizing radiation;

(b) At low doses and dose rates, the effects of ionizing radiation on the immune system may be suppressive or stimulatory. The long-term impacts of low radiation doses

on the immune functions in relation to human health need to be evaluated.

37. Annex D to the 2006 report discusses some possible mechanisms by which radiation can induce alterations in the immune system and their role in the promotion and control of cancer. The immune system is able to remove aberrant cells that are potentially capable of forming tumours. It is unclear whether cancer results from a deficiency of the immune system. Immune dysfunction, however, has been associated with several types of human tumour. Understanding the interactions of ionizing radiation with the immune system may open new possibilities for cancer prevention and treatment.

38. Annex D to the 2006 report describes studies of the effects of ionizing radiation on the human immune system for Japanese atomic bombing survivors, Chernobyl workers and residents, Techa river residents, the population near the Hanford nuclear site and patients undergoing radiotherapy. A cross-comparison of these data indicates some common findings: impairment of cellular immunity, increased humoral immunity and a shift towards an inflammatory profile. Atomic bombing survivors show perturbations to stable immune systems; this was not evident in workers and residents exposed to radiation resulting from the Chernobyl accident.

39. While the suppressive effects of high doses of ionizing radiation are well documented, annex D to the 2006 report concludes that uncertainty exists regarding the effects of low radiation doses on the immune system; both stimulatory and suppressive effects have been reported.

E. Sources-to-effects assessment for radon in homes and workplaces

40. Everyone is exposed in daily life to radon, a chemically inert radioactive gas that occurs naturally and is present in the atmosphere everywhere. Levels of radon indoors vary widely both within countries and between countries, with (nominal) geometric mean concentrations of radon in indoor air ranging from less than 10 becquerel per cubic metre (Bq m^{-3}) in the Middle East to more than 100 Bq m^{-3} in several European countries.

41. The annual per capita dose from inhalation of radon gas (and its decay products) represents typically about half of the effective dose received by members of the public from all natural sources of ionizing radiation. For certain occupations, radon gas is the predominant source of occupational radiation exposure. In the nuclear fuel cycle, the release of radon from uranium mine tailings makes a substantial contribution to the effective dose from this practice.

42. Radon and its decay products are well established as lung carcinogens. However, the doses to other organs and tissues arising from the inhalation of radon and its decay products are quite small, usually at least an order of magnitude smaller than the doses to the lung. Moreover, epidemiological data provide little evidence for increased risks of mortality other than for that due to lung cancer.

43. Annex E to the 2006 report, entitled "Sources-to-effects assessment for radon in homes and workplaces", discusses potential sources of exposure to radon for workers and the public; issues of current interest in radon dosimetry; information from animal experiments and experiments at the cellular and sub-cellular level, which are important in understanding mechanisms of carcinogenesis; epidemiological studies of miners' exposure and residential exposure to radon; and approaches to risk projection.

44. For general risk management, a factor for calculating the dose from a given exposure to radon is needed for regulatory purposes and to allow comparison with other sources of radiation exposure. There are two approaches for deriving this so-called dose factor. A "dosimetric approach" derives the dose from a given exposure on the basis of atmospheric and breathing characteristics relevant for radon and its decay products. An "epidemiological approach" has been used by ICRP to derive the factor from epidemiological studies using the ratio of the risk of lung cancer in miners to the overall risk of cancer in the atomic bombing survivors. In the Committee's 2000 report there appeared to be a difference of a factor of about two between the results for the two approaches. However, the most recent data published on the risks to underground miners (derived from updated studies of cohorts of uranium miners) suggest that the results for the two approaches are less different than initially thought. Nonetheless, more work is necessary to better understand and account for the influence of modifying factors—such as the time since exposure, the attained age and the influence of dose rate—and of confounding factors (especially tobacco smoking).

45. Studies of miners exposed to radon and its decay products provide a direct basis for assessing their lung cancer risk. The United States National Research Council's Committee on Health Risks of Exposure to Radon in its sixth report in the study series Biological Effects of Ionizing Radiation (BEIR VI), entitled *Health Effects of Exposure to Radon*, reported an excess relative risk from exposure to radon that was equivalent[7] to 1.8 per cent per megabecquerel hours per cubic metre (MBq h m^{-3}) (95 per cent confidence interval: 0.3, 35) for miners with cumulative exposures below 30 MBq h m^{-3}. There are various sources of error in the assessment of miners' exposures, especially for the earliest years of mining when exposures were highest. Other factors that complicate the analyses of data on

[7] Equilibrium equivalent concentration using Système International (SI) units. Most historic, and indeed current, measurements of exposure to radon in mines are expressed in terms of the so-called working level month (WLM). 1 WLM is equivalent to 0.637 MBq h m^{-3}.

miners include the high percentage of miners who smoke; workplace exposure to dust contaminants, such as arsenic, diesel exhaust in the dust and other pollutants; and periods spent working in non-uranium mines. The power to detect any excess risks in miners nowadays is likely to be small, in part because the exposures are much smaller than in the early years of mining and in part because of improved monitoring and record-keeping. Because of the high exposures in the early days of mining, it is possible to detect trends in the risk of lung cancer and to investigate factors that affect the dose-response relationship, such as the age at exposure, the effect of dose rate and the reduction of risk with increasing time since exposure, as well as the effect of confounding factors such as smoking.

46. The BEIR VI model developed from the pooled analysis of 11 cohorts of underground miners provides a well-established basis for estimating risks from exposure to radon and accounts for factors such as the reduced risk with increasing time since exposure. Since the BEIR VI report, studies of various miner cohorts have been updated and these confirm the general patterns of risk with dose and with time since exposure that were reported by BEIR VI, including updated coefficients to take account of the time since exposure. Studies of miners therefore provide a strong basis for evaluating risks from exposure to radon and for investigating the effects of modifiers to the dose-response relationship. Biological and cellular models of the multistage process of carcinogenesis are used to analyse the data from studies on miners. They offer the possibility of assessing the uncertainties in our understanding of the mechanisms for the development of cancer and in modelling the mechanisms for the purposes of risk estimation.

47. The extrapolation of radon concentrations in the air in mines to those in homes provides an indirect basis for assessing the risks from residential exposure to radon. However, there have now been over 20 analytical studies of residential radon and lung cancer. These studies typically assess the relative risk from exposure to radon on the basis of estimates of residential exposure over a period of 25 to 30 years prior to diagnosis of lung cancer. Recent pooled analyses of residential case control studies support a small but detectable lung cancer risk from residential exposure and this risk increases with increasing exposure. The excess relative risk from long-term residential exposure to radon at 100 Bq m^{-3} is established with reasonably good precision and is considered to be about 0.16 (after correction for uncertainties in exposure assessment) with about a three-fold factor of uncertainty higher or lower than that value. Because of the synergistic interaction between the effects of radon exposure and those of inhalation of tobacco smoke, smokers account for nearly 90 per cent of the population-averaged risk from residential exposure to radon.

48. Although there are major uncertainties in extrapolating the risks of exposure to radon from the studies of miners to assessing risks in the home, there is remarkably good agreement between the risk factors derived from studies of miners and those derived from residential case control studies. The recent pooling of residential case control studies in Europe and North America now provides a direct method for estimating the risks from long-term residential exposure to radon. On the basis of current information, the Committee considers the use of measurement-adjusted risk coefficients from pooling studies to be an appropriate basis for estimating the risks to people at home due to exposure to radon.

Appendix I

MEMBERS OF NATIONAL DELEGATIONS ATTENDING THE FIFTIETH TO FIFTY-FOURTH SESSIONS OF THE UNITED NATIONS SCIENTIFIC COMMITTEE ON THE EFFECTS OF ATOMIC RADIATION

ARGENTINA	A. J. González (Representative), D. Beninson (Representative), P. Gisone (Representative), M. del Rosario Pérez
AUSTRALIA	P. A. Burns (Representative), S. Solomon, P. Thomas
BELGIUM	J. R. Maisin (Representative), H. Bosmans, A. Debauche, H. Engels, J. Lembrechts, P. Smeesters, J. M. Van Dam, H. Vanmarcke, A. Wambersie, H. Bijwaard, R. O. Blaauboer, M. J. Brugmans
BRAZIL	D. R. Melo (Representative), J. L. Lipsztein (Representative), E. R. Rochedo
CANADA	N. E. Gentner (Representative), R. P. Bradley, K. Bundy, D. B. Chambers, R. M. Chatterjee (Representative), R. J. Cornett, R. Lane, C. Lavoie, S. Vlahovich (Representative), D. Whillans
CHINA	Pan Z. (Representative), He Q., Hou P., Jia J., Li K., Li J., Liu S., Liu Q., Pan S., Shang B., Shi J., Su X., Sun J., Sun Q., Xiu B., Xuan Y., Yang G., Yang H., Yang X., Yu J.
EGYPT	M.A.M. Gomaa (Representative), A. M. El-Naggar (Representative)
FRANCE	A. Flüry-Hérard (Representative), E. Ansoborlo, A. Aurengo, D. Averbeck, M. Bourguignon, J. F. Lacronique (Representative), J. Lallemand, J. J. Leguay, C. Luccioni, R. Maximilien, A. Rannou, M. Tirmarche
GERMANY	C. Streffer (Representative), P. Jacob, A. Kellerer, J. Kiefer, G. Kirchner, W. Köhnlein, W. U. Müller, W. Weiss (Representative)
INDIA	K. B. Sainis (Representative)
INDONESIA	Z. Alatas (Representative), K. Wiharto (Representative)
JAPAN	Y. Sasaki (Representative), T. Asano, M. Doi, A. Iwama, K. Kodama, H. Kuniyoshi, T. Maeyama, M. Nakano, Y. Nakayama, O. Niwa, M. Sasaki, K. Sato, H. Tatsuzaki, S. Yoshinaga, M. Yoshizawa
MEXICO	H. Maldonado (Representative)
PERU	L. V. Pinillos Ashton (Representative)
POLAND	Z. Jaworowski (Representative), L. Dobrzyński, M. Janiak, M. Waligórski
RUSSIAN FEDERATION	L. A. Ilyin (Representative), R. M. Alexakhin, N. P. Garnyk, A. K. Guskova (Representative), V. K. Ivanov, I. I. Kryshev, B. K. Lobach, O. A. Pavlovsky, T. S. Povetnikova, M. N. Savkin, V. A. Shevchenko
SLOVAKIA	E. Bedi (Representative), P. Gaál, V. Klener, L. Tomasek, D. Viktory (Representative)
SUDAN	K.E.H. Mohamed (Representative)
SWEDEN	L. E. Holm (Representative), L. Moberg
UNITED KINGDOM OF GREAT BRITAIN AND NORTHERN IRELAND	R. Cox (Representative), S. Bouffler, R. H. Clarke (Representative), G. M. Kendall, T. McMillan, C. Muirhead, P. Shrimpton, J. W. Stather
UNITED STATES OF AMERICA	F. A. Mettler Jr. (Representative), L. R. Anspaugh, B. G. Bennett, J. D. Boice Jr., N. H. Harley, E. V. Holahan Jr., C. B. Meinhold, R. J. Preston, H. Royal, P. B. Selby, A. G. Sowder

SECRETARIAT OF THE UNSCEAR

N. E. Gentner
M. J. Crick

Appendix II

SCIENTIFIC STAFF AND CONSULTANTS COOPERATING WITH THE UNITED NATIONS SCIENTIFIC COMMITTEE ON THE EFFECTS OF ATOMIC RADIATION IN THE PREPARATION OF THE 2006 REPORT

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