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Report of the United Nations Scientific Committee on the Effects of Atomic Radiation

Sixty-third session
(27 June-1 July 2016)

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Report of the United Nations Scientific Committee on the Effects of Atomic Radiation

Corrigendum

Paragraph 48

The fourth sentence *should read*

With regard to the construction phase of the electricity-generating technologies, by far the largest collective dose to workers per unit of electricity generated was found in the solar power cycle, followed by the wind power cycle.

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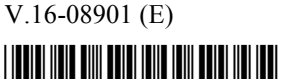

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Note

Symbols of United Nations documents are composed of letters combined with figures. Mention of such a symbol indicates a reference to a United Nations document.

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Chapter I

Introduction

1. Since the establishment 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 assessments of the sources of ionizing radiation and its effects on human health and the environment.[1] In pursuit of its mandate, the Committee thoroughly reviews and evaluates global and regional exposures to radiation. The Committee also evaluates evidence of radiation-induced health effects in exposed groups and advances in the understanding of the biological mechanisms by which radiation-induced effects on human health or on non-human biota can occur. Those assessments provide the scientific foundation used, inter alia, by the relevant agencies of the United Nations system in formulating international standards for the protection of the general public, workers and patients against ionizing radiation;[2] those standards, in turn, are linked to important legal and regulatory instruments.

2. Exposure to ionizing radiation arises from naturally occurring sources (such as radiation from outer space and radon gas emanating from rocks in the Earth) and from sources with an artificial origin (such as medical diagnostic and therapeutic procedures; radioactive material resulting from nuclear weapons testing; energy generation, including by means of nuclear power; unplanned events such as the nuclear power plant accidents at Chernobyl in 1986 and that following the great east-Japan earthquake and tsunami of March 2011; and workplaces where there may be increased exposure to radiation from artificial or naturally occurring sources).

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[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). The Committee was originally composed of the following Member States: Argentina, Australia, Belgium, Brazil, Canada, Czechoslovakia (later succeeded by Slovakia), Egypt, France, India, Japan, Mexico, Sweden, Union of Soviet Socialist Republics (later succeeded by the Russian Federation), 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 (later succeeded by 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. In its resolution 66/70 of 9 December 2011, the Assembly further enlarged the membership of the Committee to 27 and invited Belarus, Finland, Pakistan, the Republic of Korea, Spain and Ukraine to become members.

[2] For example, the international basic safety standards for radiation protection and safety of radiation sources, currently co-sponsored by the European Commission, the Food and Agriculture Organization of the United Nations, the International Atomic Energy Agency, the International Labour Organization, the Nuclear Energy Agency of the Organization for Economic Cooperation and Development, the Pan American Health Organization, the United Nations Environment Programme and the World Health Organization.

Chapter II

Deliberations of the United Nations Scientific Committee on the Effects of Atomic Radiation at its sixty-third session

3. The Committee held its sixty-third session in Vienna from 27 June to 1 July 2016.[3] Yoshiharu Yonekura (Japan), Chair; John Hunt (Brazil), Peter Jacob (Germany) and Hans Vanmarcke (Belgium), Vice-Chairs; and Michael Waligórski (Poland), Rapporteur, served as officers of the Committee.

4. The Committee took note of General Assembly resolution 70/81 on the effects of atomic radiation. It recalled that it had expected to report its long-term strategic directions beyond the period covered by its present strategic plan (2014-2019), so as to help to inform future deliberations of the Assembly on the Committee's membership.

A. Completed evaluations

5. The Committee discussed four substantive evaluations in detail, adopted the scientific report based on the findings of those evaluations (see chapter III) and requested that the scientific annexes be published in the usual manner, subject to the agreed modifications.

6. The Committee had decided, at its fifty-sixth session, to initiate work on a new estimation of human exposures to ionizing radiation from electricity generation. Accordingly it had decided to review and update its previous methodology for estimating public exposures from discharges published in its 2000 report. The Committee discussed and approved for publication the scientific annex updating the methodology and associated electronic workbooks.

7. The Committee recalled that progress on the scientific annex on radiation exposures from electricity generation had been hampered by, among other things, gaps in data on occupational exposures and on releases associated with electricity generated from non-nuclear energy sources. In comparison, there were abundant data for the nuclear energy industry, although those data remained somewhat deficient as regards decommissioning and other aspects of the so-called back end of the nuclear fuel cycle. The evaluation has been completed on the basis of reasonable and transparent assumptions where precise data were not available. The electronic workbooks for implementing the methodology had been used in 2015 to complete, in an internally consistent manner, the assessment of radiation exposures of populations from various types of electricity generation.

8. At its fifty-sixth session, held from 10 to 18 July 2008, during deliberations on its future programme of work, the Committee had decided that work should be undertaken to address radiation doses and the risks and effects from internally deposited radionuclides. At its fifty-seventh session, held from 16 to 20 August 2010,

[3] The sixty-third session was attended by observers for the International Atomic Energy Agency, the International Labour Organization, the World Health Organization, the European Union, the International Agency for Research on Cancer, the International Commission on Radiological Protection and the International Commission on Radiation Units and Measurements.

the Committee had further decided to focus on tritium and radioisotopes of uranium. At the current session, the Committee agreed that the review of the literature was now complete, that the material had been streamlined and its structure harmonized, and that final conclusions had been drawn from the material evaluated. The Committee accordingly approved the evaluations for publication.

B. Present programme of work

1. Developments since the Committee's 2013 report on the levels and effects of radiation exposure due to the nuclear accident following the great east-Japan earthquake and tsunami

9. The Committee recalled its assessment of the exposures and effects due to the nuclear accident after the 2011 great east-Japan earthquake and tsunami, as presented in its report to the sixty-eighth General Assembly in 2013 (A/68/46) and the supporting detailed scientific annex.[4] It had concluded in that report that, in general, doses were low and that therefore associated risks were also likely to be low. Cancer rates were expected to remain stable. Nevertheless, in the report the Committee had noted a possibility that the risk of thyroid cancer among those children most exposed to radiation could increase. However, it also noted that the likelihood of a large number of radiation-induced thyroid cancers in Fukushima Prefecture — such as after the Chernobyl accident — could be discounted because absorbed doses to the thyroid after the Fukushima accident were substantially lower. It had concluded that no discernible changes in the incidence of birth defects and hereditary disease were expected, and that the effects on terrestrial and marine ecosystems would be transient and localized. Cancer rates for workers were expected to remain stable.

10. Following its assessment, the Committee put in place arrangements for follow-up activities to enable it to remain abreast of additional relevant information as it was published. The Committee's report of its sixty-second session to the seventieth General Assembly included the findings from the follow-up activities it had conducted up to that time.

11. The Committee continued to identify further information that had become available up to the end of 2015, and systematically appraised relevant new publications to assess their implications for its 2013 report. A notable publication was the report by the International Atomic Energy Agency (IAEA) on the accident at the Fukushima Daiichi nuclear power station.[5] It describes the accident and its causes, evolution and consequences based on an evaluation of data and information from a large number of sources available at the time it was written. That report and a large proportion of the new publications again confirmed the main assumptions and findings in the Committee's 2013 report. None of the publications materially affected the main findings in the 2013 report or challenged its major assumptions. Several publications were identified for which further analysis or more conclusive evidence from additional research was needed. On the basis of the material reviewed, the Committee saw no need, at the current time, to make any change to its

[4] United Nations publication, Sales No. E.14.IX.1.

[5] International Atomic Energy Agency, *The Fukushima Daiichi Accident: Report by the Director General* (GC(59)/14), accompanied by technical volumes 1-5.

overarching conclusions. However, several of the research needs identified by the Committee had yet to be addressed fully by the scientific community.

12. The Committee plans to continue to identify and systematically appraise new information on the accident, and evaluate the outcomes periodically at its annual sessions. It also plans to actively engage with those responsible for formulating, implementing and advising on major research programmes in Japan, in order to rapidly assimilate emerging issues, and highlight questions needing further research. At an appropriate time, dependent on the outcomes, the Committee expects to consider the need to update its 2013 report.

13. The Committee requested the secretariat, subject to available resources, to publish the findings of its systematic review of new scientific literature as a non-sales publication in English and also to foster its publication in Japanese.

2. Cancer epidemiology of exposures at low dose-rates due to environmental radiation

14. The Committee discussed progress on an evaluation of epidemiological studies of cancer incidence from low-dose-rate exposures due to environmental sources of radiation. The Committee acknowledged that the scientific review had improved considerably. It welcomed the development of an appendix on quality criteria for the Committee's reviews of epidemiological studies. The Committee requested that the scientific review and quality criteria now be brought into accordance with each other. It requested that the appendix be finalized for publication as an independent annex because of its wider application, and expected that both the review and quality criteria could be approved for publication at the sixty-fourth session.

3. Selected evaluations of health effects and risk inference from radiation exposure

15. The Committee considered progress on evaluations of selected health effects and the inference of risk from exposure to ionizing radiation. Four scenarios were proposed for evaluation based on agreed criteria and preliminary literature reviews: leukaemia after exposure at low dose; solid cancer risk after acute and protracted exposure; thyroid cancer risk after exposure during childhood or adolescence; and risk of circulatory diseases after acute and protracted exposure. The Committee expected that the evaluations would be conducted in line with quality criteria for the Committee's reviews of epidemiological studies, and expected to discuss draft evaluations at the sixty-fourth session.

4. Collection of data on radiation exposures, in particular on medical and occupational exposures

16. The Committee took note of a progress report by the secretariat on the collection, analysis and dissemination of data on radiation exposures, in particular on medical and occupational exposures. The Committee welcomed the fact that the General Assembly, in its resolution 70/81, had encouraged Member States to nominate a national contact person to facilitate coordination of the collection and submission of data on the exposure of the public, of workers and of patients. Fifty-one Member States had nominated national contact persons by the sixty-third session of the Committee.

17. In 2014, the secretariat had launched an online platform for the collection of data on medical exposures and had invited all Member States to take part in the Committee's Global Survey of Medical Radiation Usage and Exposures. In preparation for the Global Survey it had fostered close cooperation with IAEA, the World Health Organization and the International Radiation Protection Association. Twenty countries had submitted their first data on medical exposure; however, not all their submissions were complete. Because of the relatively low response rate to date, and because of delays brought about by changes in the United Nations administrative and financial platform (Umoja), the cut-off date for data submission would be extended until May 2017. The Committee requested the secretariat to prepare a first evaluation of the results for the Committee's review at its sixty-fourth session, including a detailed literature review. It also requested the secretariat to accelerate the survey on occupational exposures, fostering close cooperation with the International Labour Organization and other relevant bodies, and to begin detailed work on defining and collecting data on public exposures to radiation from natural and artificial sources.

5. Outreach activities

18. The Committee took note of a progress report by the secretariat on outreach activities. It acknowledged in particular the work done in Japan to disseminate the Committee's 2013 report on the levels and effects of radiation exposure due to the Fukushima Daiichi accident and the white paper on developments since that report. It noted that the General Assembly had encouraged the secretariat to continue to disseminate the findings to the public. The Committee also welcomed the outreach activities surrounding the sixtieth anniversary of the Committee's inception, the thirtieth anniversary of the Chernobyl accident, and the fifth anniversary of the nuclear accident in Japan. The updated publication of the United Nations Environment Programme (UNEP) entitled *Radiation: Effects and Sources*, which is intended as a basic scientific guide for the public, was published in English; publication in other languages is envisaged. The secretariat had also prepared a memory stick preloaded with all the Committee's publications and all the resolutions relevant to its activities, in all official languages of the United Nations where available, as a handy reference tool.

19. With regard to the sixtieth anniversary 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. The Secretary-General of the United Nations, Ban Ki-moon, sent a video message for the occasion, in which he said: "From assessing the significance of fallout in the 1950s to evaluating the effects of radiation on the human genome today, the Committee has always taken an independent and impartial approach. This is crucial on issues that are often highly emotional and political." Other speakers delivered messages from the heads of their organizations, including the World Health Organization, IAEA, the Preparatory Commission for the Comprehensive Nuclear-Test-Ban Treaty Organization and UNEP. The messages commended the Committee for the expertise and independence shown in its scientific reviews, lauded its efforts to share its scientific findings with a broader audience and encouraged it to further enhance those efforts.

C. Long-term strategic directions

20. The Committee considered its long-term strategic directions beyond the period covered by its present strategic plan (2014-2019). The Committee took note of the report of the Secretary-General to the General Assembly at its sixty-ninth session on the impact of the increase in the membership to 27 States, and possible approaches to further increase procedures (see A/69/350). The Committee also took note of General Assembly resolution 70/81 on the effects of atomic radiation, in which the Assembly requested the Secretary-General to provide it at its seventy-second session with a list of the Member States that had expressed their particular interest in membership in the Committee between the sixty-sixth and seventy-second sessions.

21. The Committee envisages to direct its future work mainly at the following scientific areas:

(a) Improving the evaluation of exposure levels for people in everyday life, in occupational environments, during medical procedures, and as a result of accidents;

(b) Improving the understanding of mechanisms of radiation action and biological reaction at all levels of biological organization, i.e. from the molecular level to the population level;

(c) Obtaining more definitive evidence relating to health effects, in particular health effects from low-dose-range and chronic exposure, and sound estimates of the health implications of exposure of populations to radiation.

22. The Committee also expects that rapidly emerging issues or significant events may lead to short-term or longer-term reprioritization, and the programme of work is changed accordingly at each session. As an example, in recent times the Committee redirected its efforts towards a timely scientific evaluation of the levels and effects of radiation exposure due to the 2011 nuclear accident in Japan.[4]

23. The Committee is of the view that it will be able to continue delivering authoritative scientific evaluations in the scientific areas outlined above. The Committee fully supports the Secretary-General's view that the primary purpose of any increase in the number of States members should be to enhance the capability of the Committee to conduct its scientific work. The Committee believes that there is a limit of about 30 States members with which the Committee's secretariat at its present size could reasonably cope while at the same time supporting the scientific work of the Committee. Any increase above that number would require further strengthening of the secretariat's human resources (see paragraphs 35 and 40 of A/69/350).

24. The Committee thus considers that any discussion of membership should focus on the Committee's ability to continue its delivery of authoritative scientific evaluations as well as on the secretariat's ability to support the Committee in doing so. However, in view of the ever-increasing scientific database it may be necessary to implement a range of strategies that will support the Committee's efforts to serve the scientific community as well as wider audiences. Such strategies may also allow for the inclusion of scientists outside the Committee's current membership. There already are examples of such arrangements, and they have proved beneficial to the

Committee's work while causing only minor or negligible additions to the workload of the secretariat.

25. While recognizing the importance of including all States members in, inter alia, the implementation of the Committee's strategies, future deliberations and the production of scientific documents, and while giving due regard to available resources, the Committee could consider including the following in the strategies referred to in the previous paragraph:

(a) Establishing standing working groups focused on areas such as sources and exposure, or health and environmental effects;

(b) Inviting, on an ad hoc basis, scientists from other States Members of the United Nations to participate in evaluations regarding the above areas;

(c) Increasing the Committee's efforts to present its evaluations, and summaries thereof, in a manner that attracts readers without compromising scientific rigour and integrity;

(d) While maintaining its lead in providing authoritative scientific evaluations to the General Assembly, liaising closely with other relevant international bodies to avoid duplication of efforts to the extent possible.

26. Over the coming sessions, the Committee will work towards implementing the above strategies.

D. Future programme of work

27. The Committee discussed preliminary plans for five projects and two smaller activities. The five topics for which projects were proposed were: (a) second cancers after radiotherapy; (b) assessment of the impact on biota of radiation exposure due to the nuclear industry; (c) biological mechanisms that may influence health effects from low-dose radiation exposure; (d) effects of exposure to radon in homes and workplaces; and (e) epidemiological studies of radiation and cancer. Having considered the current work programme and the capacity of both the Committee and its secretariat, the Committee decided:

(a) To start projects in 2016 based on topics (c) and (d), and to focus the project for topic (c) on cancer and hereditary effects;

(b) To start a project in 2017 based on the proposal for topic (e) in a version further elaborated by the delegation of the United States of America;

(c) To ask the French delegation to elaborate working material for a more in-depth discussion on the proposal for topic (a) with a view to accepting the proposal in 2017.

28. The Committee also requested the secretariat to prepare a short paper on the scientific view of the Committee on the dose and dose rate effectiveness factor, and another on the evaluation of thyroid cancer data in regions affected by the nuclear power plant accident at Chernobyl in 1986, with a view to discussion and acceptance at the sixty-fourth session of the Committee.

E. Administrative issues

29. The Committee recognized that, because of the need to maintain the intensity of its work — particularly its work to develop exposure databases and to improve the dissemination of its findings to the public, including in official languages of the United Nations other than English — regular pledges to make voluntary contributions to the general trust fund established by the Executive Director of UNEP would be pivotal. The Committee suggested that the General Assembly might encourage Member States to consider making regular pledges of voluntary contributions to the general trust fund for that purpose, or to make contributions in kind.

30. The Committee agreed to hold its sixty-fourth session in Vienna from 29 May to 2 June 2017. It elected new officers to guide the Committee at its sixty-fourth and sixty-fifth sessions: Hans Vanmarcke (Belgium), Chair; Peter Jacob (Germany), Patsy Thompson (Canada), Michael Waligórski (Poland), Vice-Chairs; and Gillian Hirth (Australia), Rapporteur.

Chapter III

Scientific report

31. Four scientific annexes (published separately) provide the rationale for the findings set out below.

A. Methodology for estimating public exposures due to radioactive discharges

32. From time to time, the Committee has undertaken estimations of public exposures from radioactive discharges to the environment under normal operations, primarily from facilities in the nuclear fuel cycle. On each occasion, the Committee reviewed its methodology for estimating exposures in the light of scientific developments and, where appropriate, revised it. The Committee decided to update and extend its past evaluations of human exposures to ionizing radiation from electricity generation. Consequently, the Committee has reviewed and updated its previous methodology for estimating public exposures from discharges that had been published in its 2000 report. Because of the need to be applied more flexibly for different types of electricity generation and in the interest of transparency, the methodology was updated to provide results in terms of estimated radiation doses specific to the discharge of each significant radionuclide.

33. The updated methodology can be used to estimate characteristic individual doses and collective doses resulting from discharges to the atmosphere, rivers and lakes, and the sea. Characteristic individual doses are doses indicative of those received by a typical person living in the area around the discharge point. A collective dose is the product of the mean dose to a specified population from a particular source, and the number of people in that population, integrated over a defined period of time. In other words, a collective dose is the dose received by all members of a particular population combined, over a defined period of time. However, the calculated doses are metrics to be used only for the comparison of different sources of exposure, not to estimate implications for health. Moreover, the methodology applies only to routine discharges that can be assumed to be continuous; more sophisticated methodologies are needed to assess exposures from accidental releases.

34. Radioactive discharges can lead to exposures of the public in a number of ways, and the updated methodology takes the most important of these into account, namely exposures from radionuclides external to the body, i.e., in the atmosphere and on the ground, and exposures from radionuclides inside the body following intakes by inhalation and ingestion. To enable the estimation of exposures for both nuclear and non-nuclear forms of electricity generation, the methodology was extended to cover a wide range of radionuclides. The methodology uses models based on experimental data and other field observations in order to estimate the transfer of radionuclides through the environment and thus the resulting exposures of the public. The updated methodology now takes into account an additional route of exposure not previously considered, namely the ingestion of crops irrigated with water that contains radionuclides as a consequence of discharges to fresh water.

35. In the past, world average values for population densities and food consumption were used because those were considered sufficient to estimate global exposures from nuclear facilities. However, non-nuclear power stations are found throughout the world, and population densities and food consumption vary much more around them. Therefore the Committee has decided to include regional factors. Even so, the regions now considered are still very large, and other approaches would be necessary to make assessments for individual sites. Exposures are estimated using a series of mathematical models, for which the Committee has chosen parameter values that result in realistic exposure estimates. This is in contrast to a more cautious approach often used for regulatory purposes, whereby values are selected so as to deliberately overestimate exposures.

36. As before, estimates can still be made of collective doses to populations on a local, regional and global scale, as appropriate. In addition, the methodology provides information on collective doses resulting from a year's continuous discharge into the atmosphere to different population groups as a function of their distance from the discharge point. The estimates of collective doses to the world population are now available integrated over periods of 100, 500 and 10,000 years.

37. The methodology has been implemented in a series of electronic workbooks to provide transparency and facilitate use and revision by the Committee in any future studies. The workbooks contain information on the most important exposure pathways and radionuclides and are made available for download on the website of the Committee (www.unscear.org).

38. The Committee is satisfied that the updated methodology, as implemented in the workbooks, is robust, builds on the strong position of previous versions and is suitable for estimating exposures of regional and global populations from routine discharges of radionuclides to various environments.

B. Radiation exposures from electricity generation

39. The world's mix of electricity-generating technologies changes over time in response to the landscape of climatic, environmental, resource, political and economic challenges. Governments and researchers may conduct various comparative studies that take into account, among other things, the impact of different technologies on the public, on workers and on the environment. Exposure to ionizing radiation is only one of the many factors that may be taken into account as part of such assessments. However, the Committee considers that an update and extension of its past evaluations of radiation exposures of the public and of workers from electricity generation could be a useful source of information for such studies.

40. While interest in the exposure of the public and of workers to radiation due to electricity generation from nuclear power dates back to the earliest use of the technology, radiation exposures from the use of other electricity-generating technologies have not been so comprehensively studied. The Committee has periodically reviewed exposures of both the public and of workers related to electricity generation from nuclear power, and has also conducted evaluations for other forms of electricity generation, albeit to a lesser extent.[6] These evaluations

[6] *Sources and Effects of Ionizing Radiation — 1977 Report to the General Assembly, with Annexes*

have used a variety of methodologies and relied on data from industrial activities outside the nuclear sector that are not generally monitored or reported in a systematic manner, which has made meaningful comparisons between the radiation exposures from the different electricity-generating technologies challenging.

41. Assessing the collective dose from accidents was out of the scope of the evaluations of radiation exposures of the public and of workers from electricity generation; however, the Committee has conducted assessments of past accidents in its 2008 report; of the Chernobyl accident in its reports of 1988, 2000 and 2008; and of the Fukushima Daiichi nuclear accident in its 2013 report. It is difficult to make direct comparisons between exposures from accidents and those resulting from routine discharges. One of the reasons is that the distribution of doses to the public immediately after an accident is much more localized geographically, whereas the collective doses from normal operations for electricity generation are more evenly distributed over regional or global populations. Nevertheless, the collective dose to the global population from serious accidents, such as those that occurred at the Chernobyl and Fukushima Daiichi nuclear power stations, were orders of magnitude larger than the collective doses to the world population from one year's normal operation of significant technologies of electricity generation, as assessed in the study.

42. As stated above, the Committee has updated its methodology for estimating public exposures due to radioactive discharges. The methodology is now more flexible to be able to address a wider range of electricity-generating technologies. In addition to including an extensive analysis of the available data, the updated methodology provides the Committee with a sounder basis for comparative studies than was possible before. In parallel, the Committee also re-evaluated occupational exposures arising from different electricity-generating technologies, using data mainly from dosimetry records of worker exposures. These evaluations comprise the basis for the current comparative study on radiation exposures of both the public and of workers from electricity generation.

43. The Committee conducted the comparative study by investigating sources of exposure from electricity-generating technologies based on nuclear power; the combustion of coal, natural gas, oil and biofuels; and geothermal, wind and solar power. Two electricity-generating technologies (nuclear power and coal combustion) were investigated in detail, because a more robust database existed for them. The Committee evaluated the main sources of radioactive discharges from their life cycle. For the life cycle of nuclear power the sources of radioactive discharges included uranium mining, milling and mill tailings, power plant operation and reprocessing activities. For the life cycle associated with the combustion of coal those sources were coal mining, the operation of coal-fired power plants (both modern and older-style), and deposits of coal ash. For the sake

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(United Nations publication, Sales No. E.77.IX.1); *Ionizing Radiation: Sources and Biological Effects — 1982 Report to the General Assembly, with Annexes* (United Nations publication, Sales No. E.82.IX.8); *Sources, Effects and Risks of Ionizing Radiation — 1988 Report to the General Assembly, with Annexes* (United Nations publication, Sales No. E.88.IX.7); *Sources and Effects of Ionizing Radiation — 1993 Report to the General Assembly, with Scientific Annexes* (United Nations publication, Sales No. E.94.IX.2); and *Sources and Effects of Ionizing Radiation — 2000 Report to the General Assembly, with Scientific Annexes, Volume I: Sources*, (United Nations publication, Sales No. E.00.IX.3).

of simplicity we will refer to these cycles as the nuclear fuel cycle and the coal cycle, respectively.

44. To compare exposures, the Committee focused on two metrics. The first consisted of the collective doses to defined population groups resulting from one year's global and regional electricity generation by each technology, integrated over specific time periods. The second metric consisted of the relevant collective doses divided by the amount of electricity generated by each technology. The reference year used for the comparisons was 2010.

45. The Committee estimated that the contribution from the coal cycle was more than half of the total collective dose to the local and regional public from the discharges due to a single year's global electricity generation. That estimate was based on the assumption that the discharges originated from modern coal plants. The nuclear fuel cycle, on the other hand, contributed less than a fifth. The contribution from the coal cycle comes from discharges of natural radionuclides (primarily radon and its radioactive progeny) during coal mining, combustion of coal at power plants and coal ash deposits. Similarly, almost half of the exposures of the global public from the nuclear fuel cycle result from discharges of natural radionuclides during uranium mining and milling activities. These values depend on the share of each technology in total electricity production; in 2010 the coal cycle contributed about 40 per cent, the largest amount. Although radon and its progeny are relatively important contributors to the collective doses to the public for both the nuclear fuel cycle and the coal cycle, the associated individual doses are small compared with doses due to inhalation of radon and its progeny at levels that occur naturally in homes.

46. The Committee found, however, that the contribution of a given technology to the exposures of the global public was not simply a function of how much electricity that technology generated. There were also differences in the collective doses per unit of electricity generated by each technology to take into account. In normal operations, the coal cycle gave a higher collective dose per unit of electricity generated than the nuclear cycle, and a significantly higher dose per unit of electricity produced than the other technologies evaluated, with the exception of geothermal power. Based on the limited information available about radon discharges from geothermal power plants, the collective dose per unit of electricity generated by geothermal power could be significant. However, because the use of geothermal technology is not widespread, its contribution to radiation exposures of the global public is smaller than that from the coal cycle.

47. Previous investigations into electricity generation from nuclear power have examined the contribution to public exposures made by long-lived radionuclides, such as carbon-14, which after being discharged circulate globally and continue to contribute to radiation exposures of the public centuries into the future, albeit at extremely small individual doses. The contribution of the globally circulating radionuclides to the collective dose to the global public depends on the length of time for which the collective dose is integrated. Public exposures due to one year's discharge of these globally circulating radionuclides continue to increase slowly over time. Over long integration times, such as hundreds of years, these radionuclides result in a larger collective dose to the global public from the nuclear fuel cycle than from the coal cycle.

48. The Committee also assessed occupational exposures. The largest collective dose to workers per unit of electricity generated resulted from coal mining, because of exposures to naturally occurring radionuclides. Of all the collective doses evaluated, both to the public and to workers, the exposure of workers from coal mining made the largest contribution, although it has fallen over time because of improving mining conditions. With regard to the construction phase of the electricity-generating technologies, by far the largest collective dose to workers per unit of electricity generated was found in the solar power cycle, followed by the wind power cycle. The reason for this is that these technologies require large amounts of rare earth metals, and the mining of low-grade ore exposes workers to natural radionuclides during mining.

49. The total collective dose per unit of electricity generated in the coal cycle (i.e., the dose to the global public and all exposed workers combined) was larger than that found in the nuclear fuel cycle. This held true even if long-lived globally-circulating radionuclides were integrated over 500 years. When considering the amount of electricity generated in the year 2010 by each technology, the coal cycle resulted in the largest collective dose to the global public and workers combined, followed by the nuclear fuel cycle. Of the remaining technologies, geothermal energy and the combustion of natural gas were the next largest contributors.

50. Great care should be taken when interpreting and using these results. Their only function is to provide an insight into the different magnitudes of radiation exposure resulting from each technology. They are unfit to be used as the only metric to determine whether one energy generation technology is preferable to another. As stated earlier, a number of factors determine why countries may select a certain mix of energy generation technologies. Radiation exposure is only one of them.

C. Biological effects of selected internal emitters

51. “Internal emitters” is the commonly used term for radionuclides deposited in body organs and tissues following their intake, principally by inhalation or ingestion, but also potentially through wounds or intact skin. Depending on the radionuclide concerned and the physicochemical form of the intake, internal emitters vary enormously by type, pattern and duration of their radioactive emissions and energy deposition within and between organs and tissues.

52. It is important to study exposures to internal emitters directly because the radiation from some radionuclides is short-ranged and, to varying degrees, densely ionizing. Moreover, such radionuclides may be distributed unevenly among body tissues. Consequently, the nature of the dose delivered by some internal emitters differs markedly from that delivered by radiation penetrating from external sources such as the atomic bombs detonated in Hiroshima and Nagasaki, Japan. Most of the evidence of risk from radiation comes from studies of human exposure to penetrating radiation, while very few direct data are available on the health effects from internal exposure. Therefore doses to organs from internal emitters have to be estimated using models, and risk factors are derived principally from studies on external penetrating radiation. Under those circumstances it is highly desirable to

validate the underlying assumptions by obtaining real observations of populations exposed internally to radiation from specific radionuclides.

53. In response to initiatives in a number of countries to estimate the appropriate doses from tritium and radioisotopes of uranium and understand the corresponding health effects, the Scientific Committee has reviewed the relevant information on these radionuclides. Two scientific annexes provide the rationale for the Committee's conclusions set out here.

54. Tritium (^{3}H) is a radioactive isotope of hydrogen that decays solely by low-energy beta-particle emission. It occurs both naturally, mainly as a result of interaction between cosmic-ray particles and the upper atmosphere, and artificially, in the operation of nuclear reactors and other industrial installations, as a substance used in biomedical research and, in the past, as an ingredient used in a variety of consumer products. In the future tritium is expected to be used on a large scale in fusion reactors. In the environment and at the workplace tritium is encountered mainly as tritiated water in liquid or vapour form. An aspect of environmental and food-chain transfer that warrants further investigation is the accumulation of tritium in the organic component of foodstuffs, referred to as organically-bound tritium.

55. Uranium is a naturally occurring element and is ubiquitously distributed in the environment. There are three naturally occurring radioisotopes of uranium: ^{234}U, ^{235}U and ^{238}U. These are present in rocks and soils and hence in the human diet. They decay mainly by alpha-particle emission and have very long half-lives. Internal exposures of workers to uranium are mainly the result of mining activities and its use as a nuclear fuel. In daily life, people are exposed to uranium originating mainly from drinking water and foodstuffs. Concern has been expressed over exposures of military personnel and members of the public to depleted uranium (isotope mixtures containing a low percentage of ^{235}U) used in munitions, for example by the General Assembly in its resolution 69/57 on the effects of the use of armaments and ammunitions containing depleted uranium.

56. Whereas absorbed doses to body organs as a result of exposures to external sources of radiation are calculated using anatomical models of the human body, commonly referred to as phantoms, estimating doses from internal emitters additionally requires biokinetic models that describe the behaviour of radionuclides following their intake into the body, principally by inhalation or ingestion. Such models consider the deposition of inhaled particles and vapour in the respiratory tract and the passage of ingested radionuclides through the alimentary tract. Models also represent the subsequent distribution of radionuclides to body organs and tissues from blood, their retention in those sites of deposition, and their excretion. The reliability of models used to estimate doses from individual elements and their radioisotopes depends on the quality of available experimental and human data.

57. For tritium, models are available in the form of tritiated water, representing its distribution throughout body organs and tissues according to their water content. Less information is available with which to construct adequate models for the behaviour of various forms of organically bound tritium and other tritiated compounds, including amino acids, some of which are involved in the synthesis of DNA and associated proteins. The absorption of uranium depends partly on whether it is inhaled or ingested and varies substantially according to the physical and chemical form of the uranium. Uranium absorbed to blood accumulates mainly in

the skeleton but with some retention also in the kidneys during the rapid urinary excretion of a large fraction.

58. Different types of radiation vary in their effectiveness in causing cancer and other health effects. Two broad categories of radiation are photons and charged particles such as electrons and alpha particles. Some types of charged particles are generally more effective at causing cancer per unit of absorbed dose than penetrating photons. The assessment of such differences relies largely on experimental data about their relative biological effectiveness (RBE), defined as the ratio of the absorbed dose of a reference radiation to the absorbed dose of a test radiation required to produce the same biological effect.

59. There is extensive literature on studies of RBE for tritium beta particle emissions. Values of RBE for a range of biological end points range from about unity to several-fold higher compared to gamma rays and X-rays. However, the ability to draw conclusions for carcinogenesis is limited by the very small number of relevant studies in mammals. Limited information is available that could be used to estimate RBE values for alpha-particle emissions from isotopes of uranium. However, RBE values for alpha particles depend on the particles' energy, range and the dense deposition of energy along short tracks, and the values of RBE will be largely independent of the radionuclide concerned other than when the radionuclide determines the origin within body tissues of the emission. Typical values of RBE reported for alpha particles relative to gamma rays or X-rays are around ten for the end points of liver and lung cancer, with lower values for leukaemia.

60. While the tumorigenic effects of uranium in animals are likely related to radiological toxicity due to alpha-particle emissions, some effects are clearly related to the chemical toxicity of uranium species, particularly in the kidneys. Chemical toxicity is the limiting factor determining currently acceptable levels of uranium in drinking water.

61. A number of epidemiological studies have been conducted of workers and members of the public who may have been exposed to tritium. However, none of these studies have so far been informative in showing an increased frequency of cancer in the exposed populations that could be attributed to radiation exposure from tritium. Epidemiological studies of nuclear workers have shown a weak association between exposures from uranium and rates of lung cancer, but the data are not sufficiently conclusive to demonstrate a causal relationship.

62. The Committee considered studies on the health effects of depleted uranium used in munitions for military applications. No clinically significant pathologies related to exposure from depleted uranium were found in military personnel or members of the public. This is consistent with expectations, given the low levels of measured or assessed exposures.

63. The Committee recognizes that continued research and review is needed to assess the effects of internal exposures. Further work is required to understand the effects of uneven delivery of doses from internal emitters within tissues and cells relative to the uniform delivery of doses from external exposure to penetrating radiation. The complexity of changing exposures and tissue sensitivities during in utero and early postnatal development should also be a focus for further research.

Appendix I

Members of national delegations attending the fifty-seventh to sixty-third sessions of the United Nations Scientific Committee on the Effects of Atomic Radiation

Argentina	A. J. González (Representative), A. Canoba, P. Carretto, M. di Giorgio, M. G. Ermacora
Australia	C.-M. Larsson (Representative), C. Baggoley, M. Grzechnik, G. Hirth, P. Johnston, S. B. Solomon, R. Tinker
Belarus	A. Stazharau (Representative), J. Kenigsberg (Representative), A. Nikalayenka, A. Rozhko, V. Ternov, N. Vlasova
Belgium	H. Vanmarcke (Representative), S. Baatout, H. Bijwaard, H. Bosmans, G. Eggermont, H. Engels, F. Jamar, L. Mullenders, H. Slaper, P. Smeesters, A. Wambersie, P. Willems
Brazil	J. G. Hunt (Representative), D. R. Melo (Representative), M. Nogueira Martins (Representative), D. de Souza Santos, L. Holanda Sadler Veiga, M. C. Lourenço, E. Rochedo
Canada	P. Thompson (Representative), N. E. Gentner (Representative), B. Pieterson (Representative), C. Purvis (Representative), D. Boreham, K. Bundy, D. B. Chambers, J. Chen, P. Demers, S. Hamlat, R. Lane, C. Lavoie, E. Waller, D. Whillans
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Egypt	W. M. Badawy (Representative), T. S. El-Din Ahmed Ghazey (Representative), M.A.M. Gomaa (Representative), T. Morsi
Finland	S. Salomaa (Representative), A. Auvinen, R. Bly, E. Salminen
France	L. Lebaron-Jacobs (Representative), A. Rannou (Representative), E. Ansoborlo, J.-M. Bordy, M. Bourguignon, I. Clairand, I. Dublineau Naud, A. Flüry-Hérard, J.-R. Jourdain, R. Maximilien, F. Ménétrier, E. Quémeneur, M. Tirmarche
Germany	P. Jacob (Representative), W. Weiss (Representative), S. Baechler, A. Böttger, A. A. Friedl, K. Gehrcke, T. Jung, G. Kirchner, J. Kopp, R. Michel, W.-U. Müller, W. Rühm, H. Zeeb
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Indonesia	E. Hiswara (Representative), Z. Alatas (Representative), S. Widodo (Representative), G. B. Prajogi, G. Witono, B. Zulkarnaen

Japan	Y. Yonekura (Representative), K. Akahane, M. Akashi, S. Akiba, T. Aono, N. Ban, M. Chino, H. Fujita, K. Kodama, M. Kowatari, M. Nakano, O. Niwa, K. Ozasa, S. Saigusa, K. Sakai, G. Suzuki, M. Takahashi, T. Takahashi, Y. Yamada, H. Yamagishi, H. Yasuda
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Pakistan	Z. A. Baig (Representative), M. Ali (Representative), R. Ali
Peru	A. Lachos Dávila (Representative), L. V. Pinillos Ashton (Representative), B. M. García Gutiérrez
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Ukraine	D. Bazyka (Representative)
United Kingdom of Great Britain and Northern Ireland	S. Bouffler (Representative), J. Cooper (Representative), J. Harrison (Representative), A. Bexon, J. Simmonds, R. Wakeford, W. Zhang
United States of America	R. J. Preston (Representative), F. A. Mettler Jr. (Representative), A. Ansari, L. R. Anspaugh, J. D. Boice Jr., W. Bolch, H. Grogan, N. H. Harley, E. V. Holahan Jr., B. A. Napier, D. Pawel, G. E. Woloschak

Appendix II

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