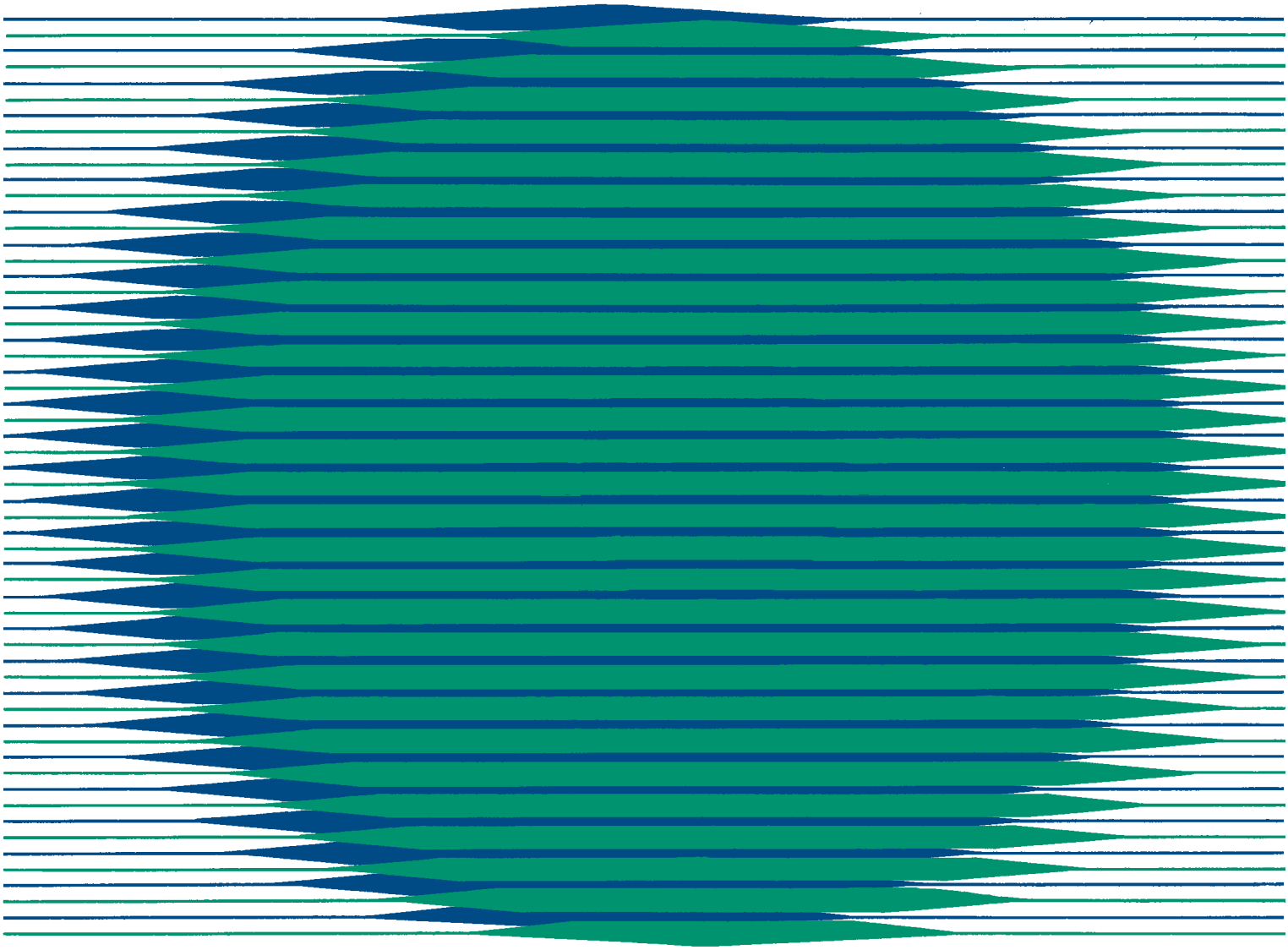
SOURCES AND EFFECTS OF IONIZING RADIATION

United Nations Scientific Committee on the Effects of Atomic Radiation
UNSCEAR 2000 Report to the General Assembly,
with Scientific Annexes

VOLUME I: SOURCES



UNITED NATIONS

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UNSCEAR 2000 Report to the General Assembly, with Scientific Annexes

UNITED NATIONS
New York, 2000

NOTE

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INTRODUCTION

1. Over the past few years, the United Nations Scientific Committee on the Effects of Atomic Radiation[1] has undertaken a broad review of the sources and effects of ionizing radiation. In the present report,[2] the Committee, drawing on the main conclusions of its scientific assessments, summarizes the developments in radiation science in the years leading up to the new millennium.

2. The present report and its scientific annexes were prepared between the forty-fourth and the forty-ninth sessions of the Committee. The following members of the Committee served as Chairman, Vice-Chairman and Rapporteur, respectively, at the sessions: forty-fourth and forty-fifth sessions: L. Pinillos-Ashton (Peru), A. Kaul (Germany) and G. Bengtsson (Sweden); forty-sixth and forty-seventh sessions: A. Kaul (Germany), L.-E. Holm (Sweden) and J. Lipsztein (Brazil); and forty-eighth and forty-ninth sessions: L.-E. Holm (Sweden), J. Lipsztein (Brazil) and Y. Sasaki (Japan). The names of members of national delegations who attended the forty-fourth to the forty-ninth sessions of the Committee as members of national delegations are listed in Appendix I.

3. The Committee wishes to acknowledge the help and advice of a group of consultants and contributors who helped in the preparation of the scientific annexes (see Appendix II). The sessions of the Committee were attended by representatives of the World Health Organization and the International Atomic Energy Agency. The International Commission on Radiation Units and Measurements and the International Commission on Radiological Protection were also represented. The Committee wishes to acknowledge their contributions to the discussions.

4. In carrying out its work, the Committee applied its scientific judgement to the material it reviewed and took care to assume an independent and neutral position in reaching its conclusions. The results of its work are presented for the general reader in this report to the General Assembly. The supporting scientific annexes are aimed at the general scientific community.

5. The United Nations Scientific Committee on the Effects of Atomic Radiation, a scientific committee of the General Assembly, is the body in the United Nations system with a mandate to assess and report levels and effects of exposure to ionizing radiation. The fact that the Committee holds this specific mandate from such an authoritative body greatly enhances its ability to provide an effective and independent service to the world. The United Nations, through the General Assembly, can take credit for providing that service. The information provided by the Committee assists the General Assembly in making recommendations, in particular those relevant to international collaboration in the health field, to sustainable development and, to some extent, to the maintenance of international peace and security.

6. New challenges as regards global levels of radiation exposure continue to arise and new biological information on the effects of radiation exposure is becoming available. For example, large amounts of radioactive waste have built up as a result of both peaceful uses of nuclear energy and military nuclear operations, and radiation sources used in military and peaceful operations have been abandoned, creating a situation that is prone to illicit trafficking and other criminal activities. Moreover, the potential risks from low-level radiation exposure, that is, exposure to radiation comparable with natural background radiation, are the cause of lively debate and controversy. The Committee is responding to those challenges and will do so further with new initiatives to be included in its future assessments of radiation sources, levels and effects..

7. Governments and organizations throughout the world rely on the Committee's evaluations of the sources and effects of radiation as the scientific basis for estimating radiation risk, establishing radiation protection and safety standards and regulating radiation sources. Within the United Nations system, those estimates are used by the International Atomic Energy Agency in discharging its statutory functions of establishing standards for the radiation protection of health and providing for their application. The Committee is proposing a renewed programme of work to fulfil its obligations to the General Assembly.

I. OVERVIEW

A. THE EFFECTS OF RADIATION EXPOSURE

8. Radiation exposure can damage living cells, causing death in some of them and modifying others. Most organs and tissues of the body are not affected by the loss of even considerable numbers of cells. However, if the number lost is large enough, there will be observable harm to organs that may lead to death. Such harm occurs in individuals who are exposed to radiation in excess of a threshold level. Other radiation damage may also occur in cells that are not killed but modified. Such damage is usually repaired. If the repair is not perfect, the resulting modification will be transmitted to further cells and may eventually lead to cancer. If the cells modified are those transmitting hereditary information to the

descendants of the exposed individual, hereditary disorders may arise.

9. Radiation exposure has been associated with most forms of leukaemia and with cancers of many organs, such as lung, breast and thyroid gland, but not with certain other organs, such as the prostate gland. However, a small addition of radiation exposure (e.g. about the global average level of natural radiation exposure) would produce an exceedingly small increase in the chances of developing an attributable cancer. Moreover, radiation-induced cancer may manifest itself decades after the exposure and does not differ from cancers that arise spontaneously or are attributable to other factors. The major long-term evaluation of populations exposed to radiation is the study of the approximately 86,500 survivors of the atomic bombings of Hiroshima and Nagasaki, Japan. It has revealed an excess of a few hundred cancer deaths in the population studied. Since approximately half of that population is still alive, additional study is necessary in order to obtain the complete cancer experience of the group.

10. Radiation exposure also has the potential to cause hereditary effects in the offspring of persons exposed to radiation. Such effects were once thought to threaten the future of the human race by increasing the rate of natural mutation to an inappropriate degree. However, radiation-induced hereditary effects have yet to be detected in human populations exposed to radiation, although they are known to occur in other species. The Committee is preparing a comprehensive report on hereditary effects of radiation exposures to be submitted to the General Assembly at its fifty-sixth session.

B. LEVELS OF RADIATION EXPOSURE

11. Everyone is exposed to natural radiation. The natural sources of radiation are cosmic rays and naturally occurring radioactive substances existing in the Earth itself and inside the human body. A significant contribution to natural exposure of humans is due to radon gas, which emanates from the soil and may concentrate in dwellings. The level of natural exposure varies around the globe, usually by a factor of about 3. At many locations, however, typical levels of natural radiation exposure exceed the average levels by a factor of 10 and sometimes even by a factor of 100.

12. Human activities involving the use of radiation and radioactive substances cause radiation exposure in addition to the natural exposure. Some of those activities simply enhance the exposure from natural radiation sources. Examples are the mining and use of ores containing naturally radioactive substances and the production of energy by burning coal that contains such substances. Environmental contamination by radioactive residues resulting from nuclear weapons testing continues to be a global source of human radiation exposure. The production of nuclear materials for military purposes has left a legacy of large amounts of radioactive residues in some parts of the world. Nuclear power plants and other nuclear installations release radioactive materials into the environment and produce radioactive waste during operation and on their decommissioning. The use of radioactive materials in industry, agriculture and research is expanding around the globe and people have been harmed by mishandled radiation sources.

13. Such human activities generally give rise to radiation exposures that are only a small fraction of the global average level of natural exposure. However, specific individuals residing near installations releasing radioactive material into the environment may be subject to higher exposures. The exposure of members of the public to regulated releases is restricted by internationally recognized limits, which are set at somewhat less than the global average level of natural exposure. It is to be noted that, should some of the sites with high levels of radioactive residues be inhabited or re-inhabited, the settlers would incur radiation exposures that would be higher than the global average level of natural exposures.

14. The medical use of radiation is the largest and a growing man-made source of radiation exposure. It includes diagnostic radiology, radiotherapy, nuclear medicine and interventional radiology. Large numbers of people (in developing countries in particular) cannot yet take advantage of many of those medical procedures, which are not available worldwide. For the time being, therefore, those people receive less radiation exposure from medical diagnosis and treatment than people living in countries benefiting from advanced medical procedures, a situation that is expected to change in the future and will need to be followed by the Committee.

15. The average levels of radiation exposure due to the medical uses of radiation in developed countries is equivalent to approximately 50% of the global average level of natural exposure. In those countries, computed tomography accounts for only a few per cent of the procedures but for almost half of the exposure involved in medical diagnosis. Severe radiation-related injuries have occurred as a result of poor practice of some interventional techniques (such as radiological procedures to monitor the dilation of coronary arteries) and radiotherapy.

16. Radiation exposure also occurs as a result of occupational activities. It is incurred by workers in industry, medicine and research using radiation or radioactive substances, as well as by passengers and crew during air travel. It is very significant for astronauts.

17. The average level of occupational exposures is generally similar to the global average level of natural radiation exposure. However, a few per cent of workers receive exposures several times higher than the average exposure to natural radiation. The exposure of workers is restricted by internationally recognized limits, which are set at around 10 times the average exposure to natural radiation.

C. THE RADIOLOGICAL CONSEQUENCES OF THE CHERNOBYL ACCIDENT

18. The accident at the Chernobyl nuclear power plant was the most serious accident involving radiation exposure. It caused the deaths, within a few days or weeks, of 30 workers and radiation injuries to over a hundred others. It also brought about the immediate evacuation, in 1986, of about 116,000 people from areas surrounding the reactor and the permanent relocation, after 1986, of about 220,000 people from Belarus, the Russian Federation and Ukraine. It caused serious social and psychological disruption in the lives of those affected and vast economic losses over the entire region. Large areas of the three countries were contaminated, and deposition of released radionuclides was measurable in all countries of the northern hemisphere.

19. There have been about 1,800 cases of thyroid cancer in children who were exposed at the time of the accident, and if the current trend continues, there may be more cases during the next decades. Apart from this increase, there is no evidence of a major public health impact attributable to radiation exposure 14 years after the accident. There is no scientific evidence of increases in overall cancer incidence or mortality or in non-malignant disorders that could be related to radiation exposure. The risk of leukaemia, one of the main concerns owing to its short latency time, does not appear to be elevated, not even among the recovery operation workers. Although those most highly exposed individuals are at an increased risk of radiation-associated effects, the great majority of the population are not likely to experience serious health consequences as a result of radiation from the Chernobyl accident.

II. SOURCES OF RADIATION EXPOSURE

20. Ionizing radiation represents electromagnetic waves and particles that can ionize, that is, remove an electron from an atom or molecule of the medium through which they propagate. Ionizing radiation may be emitted in the process of natural decay of some unstable nuclei or following excitation of atoms and their nuclei in nuclear reactors, cyclotrons, x-ray machines or other instruments. For historical reasons, the photon (electromagnetic) component of ionizing radiation emitted by the excited nucleus is termed gamma rays and that emitted from machines is termed x rays. The charged particles emitted from the nucleus are referred to as alpha particles (helium nuclei) and beta particles (electrons).

21. The process of ionization in living matter necessarily changes atoms and molecules, at least transiently, and may thus damage cells. If cellular damage does occur and is not adequately repaired, it may prevent the cell from surviving or reproducing or performing its normal functions. Alternatively, it may result in a viable but modified cell.

22. The basic quantity used to express the exposure of material such as the human body is the absorbed dose, for which the unit is the gray (Gy). However, the biological effects per unit of absorbed dose varies with the type of radiation and the part of the body exposed. To take account of those variations, a weighted quantity called the effective dose is used, for which the unit is the sievert (Sv). In reporting levels of human exposure, the Committee usually uses the effective dose. In the present report, both the absorbed dose and the effective dose are usually simply called “dose”, for which the units provide the necessary differentiation. A radioactive source is described by its activity, which is the number of nuclear disintegrations per unit of time. The unit of activity is the becquerel (Bq). One becquerel is one disintegration per second.

23. To evaluate the effects of exposing a defined population group, the sum of all doses acquired by the members of the group, termed the “collective dose” (in units of man Sv), may be used. The value of the collective dose divided by the number of individuals in the exposed population group is the per caput dose, in Sv. The general procedures used by the Committee to evaluate radiation doses are presented in Annex A of this report, “Dose assessment methodologies”.

A. NATURAL RADIATION EXPOSURES

24. All living organisms are continually exposed to ionizing radiation, which has always existed naturally. The sources of that exposure are cosmic rays that come from outer space and from the surface of the Sun, terrestrial radionuclides that occur in the Earth’s crust, in building materials and in air, water and foods and in the human body itself. Some of the exposures are fairly constant and uniform for all individuals everywhere, for example, the dose from ingestion of potassium-40 in foods. Other exposures vary widely depending on location. Cosmic rays, for example, are more intense at higher altitudes, and concentrations of uranium and thorium in soils are elevated in localized areas. Exposures can also vary as a result of human activities and practices. In particular, the building materials of houses and the design and ventilation systems strongly influence indoor levels of the radioactive gas radon and its decay products, which contribute significantly to doses through inhalation.

25. The components of the exposures resulting from natural radiation sources have been reassessed in this report based on new information and data from measurements and on further analysis of the processes involved. The results are presented

in Annex B, "Exposures from natural radiation sources". The exposure components have been added to provide an estimate of the global average exposure. The average global exposure does not pertain to any one individual, since there are wide distributions of exposures from each source and the consequent effective doses combine in various ways at each location, depending on the specific concentration of radionuclides in the environment and in the body, the latitude and altitude of the location and many other factors.

26. The annual worldwide per caput effective dose is determined by adding the various components, as summarized in Table 1. The annual global per caput effective dose due to natural radiation sources is 2.4 mSv. However, the range of individual doses is wide. In any large population about 65% would be expected to have annual effective doses between 1 mSv and 3 mSv, about 25% of the population would have annual effective doses less than 1 mSv and 10% would have annual effective doses greater than 3 mSv.

Table 1
Average radiation dose from natural sources

Source	*Worldwide average annual effective dose (mSv)*	*Typical range (mSv)*
External exposure		
Cosmic rays	0.4	0.3-1.0 [a]
Terrestrial gamma rays	0.5	0.3-0.6 [b]
Internal exposure		
Inhalation (mainly radon)	1.2	0.2-10 [c]
Ingestion	0.3	0.2-0.8 [d]
Total	2.4	1-10

a Range from sea level to high ground elevation.
b Depending on radionuclide composition of soil and building materials.
c Depending on indoor accumulation of radon gas.
d Depending on radionuclide composition of foods and drinking water.

B. MAN-MADE ENVIRONMENTAL EXPOSURES

27. Releases of radioactive materials to the environment and exposures of human populations have occurred in several activities, practices and events involving radiation sources. Assessment of the resulting exposures is presented in Annex C of this report, "Exposures to the public from man-made sources of radiation". The main man-made contribution to the exposure of the world's population has come from the testing of nuclear weapons in the atmosphere, from 1945 to 1980. Each nuclear test resulted in unrestrained release into the environment of substantial quantities of radioactive materials, which were widely dispersed in the atmosphere and deposited everywhere on the Earth's surface.

28. The Committee has given special attention to the evaluation of the doses from nuclear explosions in the atmosphere. The worldwide collective effective dose from that practice was evaluated in the UNSCEAR 1982 Report based on numerous measurements of the global deposition of ^{90}Sr and ^{137}Cs and of the occurrence of those and other fallout radionuclides in diet and the human body that were made at the time the testing was taking place.

29. New information has become available on the numbers and yields of nuclear tests. Those data were not fully revealed earlier by the countries that conducted the tests because of military sensitivities. An updated listing of atmospheric nuclear tests conducted at each of the test sites is included in this report (see Annex C). Although the total explosive yields of each test have been divulged, the fission and fusion yields are still mostly suppressed. Some general assumptions have been made to make it possible to specify the fission and fusion yields of each test in order to estimate the amounts of radionuclides produced in the explosions. The estimated total of fission yields of individual tests is in agreement with the global deposition of the main fission radionuclides ^{90}Sr and ^{137}Cs, as determined by worldwide monitoring networks.

30. With improved estimates of the production of each radionuclide in individual tests and using an empirical atmospheric transport model, it is possible to determine the time course of the dispersion and deposition of radionuclides and to estimate the annual doses from various pathways in each hemisphere of the world. In that way it has been calculated that the world average annual effective dose reached a peak of 150 μSv in 1963 and has since decreased to about 5 μSv in 2000, from residual radionuclides in the environment, mainly ^{14}C, ^{90}Sr and ^{137}Cs. The average annual doses are 10% higher in the northern hemisphere, where most of the testing took place, and lower in the southern hemisphere. Although there was considerable concern at the time of testing, the annual doses remained relatively low, reaching at most about 7% of the background level from natural radiation sources.

31. The exposures of local populations surrounding the test sites have also been assessed using available information. The level of detail is still not sufficient to document the exposures with great accuracy. Attention to the local conditions and the possibilities of exposure was not great in the early years of the test programmes. However, dose reconstruction efforts are proceeding to clarify this experience and to document the local and regional exposures and doses that occurred.

32. Underground testing caused exposures beyond the test sites only if radioactive gases leaked or were vented. Most underground tests had much lower yields than atmospheric tests, and it was usually possible to contain the debris. Underground tests were conducted at the rate of 50 or more per year from 1962 to 1990. Although it is the intention of most countries to agree to ban all further tests, both atmospheric and underground, the Comprehensive Nuclear-Test-Ban Treaty (see General Assembly resolution 50/245) has not yet come into force. Further underground testing has occurred. Thus, it cannot yet be stated that the practice has ceased.

33. During the time when nuclear weapon arsenals were being built up, especially in the earlier years (1945-1960), there were releases of radionuclides exposing local populations downwind or downstream of nuclear installations. Since there was little recognition of exposure potentials and monitoring of releases was limited, the assessment must be based on the reconstruction of doses. Results are still being obtained that document the experience. Practices have greatly improved and arsenals are now being reduced. Exposures from the military fuel cycle have thus diminished to very low levels.

34. A continuing practice is the generation of electrical energy by nuclear power reactors. Assuming this practice of generation lasts for 100 years, the maximum collective dose can be estimated from the cumulative doses that occur during the period of the practice. The normalized 100-year truncated figure is 6 man Sv per gigawatt year. Assuming the present annual generation of 250 gigawatt years continues, the truncated collective dose per year of practice is 1,500 man Sv to the world population, giving an estimated maximum per caput dose of less than 0.2 μSv per year.

35. Except in the case of accidents or at sites where wastes have accumulated, causing localized areas to be contaminated to significant levels, there are no other practices that result in important exposures from radionuclides released into the environment. Estimates of releases of isotopes produced and used in industrial and medical applications are being reviewed, but these seem to be associated with rather insignificant levels of exposure. Possible future practices, such as dismantling of weapons, decommissioning of installations and waste management projects, can be reviewed as experience is acquired, but these should all involve little or no release of radionuclides and should cause only negligible doses. For medical practice, the highest individual doses, averaging about 0.5 mSv, may be received by family members who may come into close contact with patients undergoing ^{131}I treatments.

36. When accidents occur, environmental contamination and exposures may become significant. The accident at the Chernobyl nuclear power plant was a notable example. The exposures were highest in the local areas surrounding the reactor, but low-level exposures could be estimated for the European region and for the entire northern hemisphere. In the first year following the accident, the highest regionally averaged annual doses in Europe outside the former Union of Soviet Socialist Republics were less than 50% of the natural background dose. Subsequent exposures decreased rapidly. The higher doses and possible health consequences in the region of the accident are being investigated.

37. There are several industries that process or utilize large volumes of raw materials containing natural radionuclides. Discharges from those industrial plants to air and water and the use of by-products and waste materials may contribute to enhanced exposure of the general public. Estimated maximum exposures arise from phosphoric acid production, mineral sand processing industries and coal-fired power stations. Although annual doses of about 100 μSv could be received by a few local residents, doses of 1-10 μSv would be more common.

C. MEDICAL RADIATION EXPOSURES

38. The use of ionizing radiation for medical diagnosis and therapy is widespread throughout the world. There are significant country-to-country variations in national resources for and practice in medical radiology. In general, medical exposures are confined to an anatomical region of interest and dispensed for specific clinical purposes so as to be of direct benefit to the examined or treated individuals. Diagnostic exposures are characterized by fairly low doses to individual patients (effective doses are typically in the range 0.1-10 mSv) that in principle are just sufficient to provide the required clinical information. The resulting per caput doses to populations are given in Table 2. In contrast, therapeutic exposures involve very much higher doses precisely delivered to the tumour volumes (prescribed doses typically in the range 20-60 Gy) to eradicate disease, principally cancer, or to alleviate symptoms. Relatively small numbers of diagnostic or therapeutic exposures are conducted on volunteers in controlled studies for the purposes of research. Medical radiology is conducted systematically and radiation accidents are fairly infrequent.

39. The Committee has assessed the exposures from medical radiation procedures based on information obtained from questionnaires distributed to all Member States. Four levels of health care have been distinguished based on the number of physicians available to serve the inhabitants of a country. They range from one physician per 1,000 population at the highest level (health-care level I to one physician for

Table 2
Radiation exposures from diagnostic medical x-ray examinations

Health care level	*Population per physician*	*Annual number of examinations per 1,000 population*	*Average annual effective dose to population (mSv)*
I	<1 000	920	1.2
II	1 000-3 000	150	0.14
III	3 000-10 000	20	0.02
IV	>10 000	<20	<0.02
Worldwide average		330	0.4

more than 10,000 population (health-care level IV). The available data have been averaged to obtain representative frequencies of procedures or exposure within countries at each level. These were then extrapolated to the population of all countries within each level and the total population of the world and are presented in Table 2. The detailed results of the Committee's evaluation are presented in Annex D, "Medical radiation exposures".

40. Temporal trends in the estimates of the number of procedures in medical radiology from the various reviews undertaken by the Committee indicate a steady increase. Further increase in the use of medical radiation and resultant doses can be expected following changes in the patterns of health care that are being facilitated by advances in technology and economic developments. For example, increase is likely in the utilization of x rays with, in particular, a growth in importance for computed tomography and interventional procedures. Practice in nuclear medicine will be driven by the use of new and more specific radiopharmaceuticals for diagnosis and therapy, and there will be increased demand for radiotherapy owing to population ageing. In addition, further growth in medical radiology can be expected in developing countries where present facilities and services are often lacking.

41. Accordingly, there is a need for the Committee to undertake further authoritative reviews of global practice, with the systematic compilation of new national survey data, in particular from regions where knowledge is presently sparse, and the exploration of improved modelling in order to provide refined assessments of worldwide exposures. This major task will help monitor and inform on levels and trends in dose from the rapidly evolving and important practice of medical radiology and will also stimulate further assessments and critical review of practices by individual countries.

D. OCCUPATIONAL RADIATION EXPOSURES

42. There are a number of occupations in which workers are exposed to man-made sources of radiation, such as at nuclear installations or medical clinics, and some workers are exposed to enhanced levels of natural radiation. The Committee uses the term occupational exposure to mean exposures at work that are directly due to the work. Occupational radiation exposures have been assessed from data submitted to the Committee by national authorities in response to questionnaires. The data summarized in Annex E, "Occupational radiation exposures", are quite extensive. Five-year average data for various occupations are reported for 1975-1994. The exposures from man-made sources are given the most attention; countries usually record such data for regulatory purposes. Where average exposures over a workforce are needed, the number of workers is taken to be the number of workers monitored.

43. The estimates of occupational radiation exposure in this report have benefited from a much more extensive and complete database than was previously available to the Committee. The efforts by countries to record and improve dosimetric data were reflected in the responses to the Committee's survey of occupational radiation exposures and have led to improved estimates of occupational doses.

44. The Committee's current estimate of the worldwide collective effective dose to workers from man-made sources for the early 1990s, 2,700 man Sv, is lower by a factor of about 2 than that made by the Committee for the late 1970s. A significant part of the reduction comes in the nuclear power fuel cycle, in particular in uranium mining. However, reductions are seen in all the main categories: industrial uses, medical uses, defence activities and education. This trend is also reflected in the worldwide average annual effective dose, which has fallen from about 1.9 mSv to 0.6 mSv. The average annual doses to workers in the various occupations are given in Table 3.

45. No attempt has been made to deduce any trend in the estimates of dose from occupational exposure to enhanced natural sources of radiation, as the supporting data are somewhat limited. The UNSCEAR 1988 Report made a crude estimate of about 20,000 man Sv from that source, which was subsequently revised downward to 8,600 man Sv in the UNSCEAR 1993 Report. The comparable figure for 1990-1994 is 5,700 man Sv; however, an important new element has been added for this period, namely, occupational exposure to elevated levels of radon and its progeny, bringing the overall estimate of collective dose to 11,700 man Sv. This is still considered to be a crude estimate, and much better data are required. This will be a challenge for the next assessment by the Committee.

Table 3
Occupational radiation exposures

Source / practice	*Number of monitored workers (thousands)*	*Average annual effective dose (mSv)*
Man-made sources		
Nuclear fuel cycle (including uranium mining)	800	1.8
Industrial uses of radiation	700	0.5
Defence activities	420	0.2
Medical uses of radiation	2 320	0.3
Education/veterinary	360	0.1
Total from man-made sources	4 600	0.6
Enhanced natural sources		
Air travel (crew)	250	3.0
Mining (other than coal)	760	2.7
Coal mining	3 910	0.7
Mineral processing	300	1.0
Above ground workplaces (radon)	1 250	4.8
Total from natural sources	6 500	1.8

E. COMPARISON OF EXPOSURES

46. Radiation doses from the various sources of exposure received by the world population are compared in Table 4. Two quantities are appropriate for comparisons. For a source that is constant, or that changes only as the result of natural processes, the annual global per caput effective dose is used. That quantity is also used for a source that delivers all its exposure in a short time. For sources that continue to cause exposure over long periods, it is necessary to indicate the trend over time. The values given in Table 4 are the annual doses averaged over the world population, which are not necessarily the doses that any one individual would experience. Because of considerable variations in exposures, depending on location, personal habits, diet, and so on, doses to individuals differ.

Table 4
Annual per caput effective doses in year 2000 from natural and man-made sources

Source	*Worldwide annual per caput effective dose (mSv)*	*Range or trend in exposure*
Natural background	2.4	Typically ranges from 1-10 mSv, depending on circumstances at particular locations, with sizeable population also at 10-20 mSv.
Diagnostic medical examinations	0.4	Ranges from 0.04-1.0 mSv at lowest and highest levels of health care
Atmospheric nuclear testing	0.005	Has decreased from a maximum of 0.15 mSv in 1963. Higher in northern hemisphere and lower in southern hemisphere
Chernobyl accident	0.002	Has decreased from a maximum of 0.04 mSv in 1986 (average in northern hemisphere). Higher at locations nearer accident site
Nuclear power production (see paragraph 34)	0.0002	Has increased with expansion of programme but decreased with improved practice

47. By far the greatest contribution to exposure comes from natural background radiation. The annual per caput dose is 2.4 mSv and the range in typical circumstances may be between 1 mSv and 10 mSv. There are, however, small groups of persons who may be exposed to much higher levels. In some places, the natural radionuclide content in the soil creates high external exposure levels; these are known as high-background areas. Much more significant and widespread is the variability in the levels of radon concentration in indoor air.

48. The second largest contribution to exposures of individuals worldwide is from medical radiation procedures. There is an increasing trend in such exposures, reflecting the more widespread use and availability of medical radiation services throughout the world.

49. The exposure of the world's population from nuclear test explosions in the atmosphere was considered to be quite dramatic at the time of the most intensive testing (1958-1962), when it was realized how widespread it had been. The practice resulted in the unrestrained release of

large amounts of radioactive materials directly into the atmosphere. Of all man-made practices or events, atmospheric nuclear testing involved the largest releases of radionuclides into the environment. The annual doses reached, on average, 7% of the natural background at their maximum in 1963. Residual levels of longer-lived radionuclides still present in the environment contribute little to the annual exposure of the world population.

III. RADIATION-ASSOCIATED CANCER

50. Radiation effects are caused by the damage inflicted in cells by the radiation interactions. The damage may result in cell death or modifications that can affect the normal functioning of organs and tissues. Most organs and tissues of the body are not affected by the loss of even considerable numbers of cells. However, if the number lost becomes large, there will be observable harm to the organ or tissue and therefore to the individual. Only if the radiation dose is large enough to kill a large number of cells will such harm occur. This type of harm occurs in all individuals who receive an acute dose in excess of the threshold for the effect and is called “deterministic”.

51. If the cell is not killed but only modified by the radiation damage, the damage in the viable cell is usually repaired. If the repair is not perfect, the modification will be transmitted to daughter cells and may eventually lead to cancer in the tissue or organ of the exposed individual. If the cells are concerned with transmitting genetic information to the descendants of the exposed individual, hereditary disorders may arise. Such effects in the individuals or in their descendants are called “stochastic”, meaning of a random nature.

52. In short, deterministic (acute) effects will occur only if the radiation dose is substantial, such as in accidents. Stochastic effects (cancer and hereditary effects) may be caused by damage in a single cell. As the dose to the tissue increases from a low level, more and more cells are damaged and the probability of stochastic effects occurring increases.

53. Over the 45 years that the Committee has been reviewing information relating to the biological effects of radiation, substantial scientific advances have taken place and an improved understanding has resulted. The present knowledge of radiation effects and the main results of the Committee’s assessments are summarized below.

A. RADIOBIOLOGICAL EFFECTS AFTER LOW DOSES OF RADIATION

54. The Committee has reviewed the broad field of experimental studies of radiation effects in cellular systems and in plants and animals. Many of those responses and the factors modifying them form a basis for the knowledge of human radiation effects and can often be evaluated in more detail than studies of humans. Furthermore, fundamental radiobiology nowadays includes the field of molecular radiobiology, which is contributing to an understanding of the mechanisms of radiation response.

55. Damage to deoxyribonucleic acid (DNA) in the nucleus is the main initiating event by which radiation causes long-term harm to organs and tissues of the body. Double-strand breaks in DNA are regarded as the most likely candidate for causing critical damage. Single radiation tracks have the potential to cause double-strand breaks and in the absence of fully efficient repair could result in long-term damage, even at the lowest doses. Damage to other cellular components (epigenetic changes) may influence the functioning of the cell and progression to the malignant state.

56. Numerous genes are involved in cellular response to radiation, including those for DNA damage repair and cell-cycle regulation. Mutation of those genes is reflected in several disorders of humans that confer radiation sensitivity and cancer proneness on the individuals concerned. For example, mutation of one of many so-called checkpoint genes may allow insufficient time to repair damage, because the cell loses its ability to delay progression in the cell cycle following radiation exposure.

57. Cells have a number of biochemical pathways capable of recognizing and dealing with specific forms of damage. This subject is reviewed in Annex F, “DNA repair and mutagenesis”. One gene that plays a key role is the tumour suppressor *TP53*, which is lost or mutated in more than half of all human tumours. The p53 protein produced by the gene controls both arrest of the cell cycle and one pathway of apoptosis (the programmed cell death that is instrumental in preventing some damaged cells from progressing to the transformed, malignant growth stage). Some such biochemical pathways are also implicated in stress response or adaptation processes that act to limit the extent or outcome of damage. Even with such protective processes induced and acting, it is clear that misrepaired radiation damage gives the potential for progression to cancer induction or hereditary disease.

58. Proto-oncogenes (genes that may be activated inappropriately and then participate in tumorigenesis) and tumour-suppressor genes control a complex array of biochemical pathways involved in cellular signalling and interaction, growth, mitogenesis, apoptosis, genomic stability and differentiation. Mutation of those genes can compromise those controls and contribute to the multi-stage development of cancer.

59. Proto-oncogene activation by chromosomal translocation is often associated with early stages in the development of leukaemias and lymphomas, although gene loss also occurs. For many solid tumours there is a requirement for a loss-of-function mutation of tumour-suppressor genes that control cellular proliferation in specific tissues. The subsequent onset of genomic instability through further mutations in clones of cells may be a critical event in the transformation from benign to malignant state. Loss of apoptotic control is also believed to be important throughout tumorigenesis.

60. The multi-stage nature of tumorigenesis is considered in Annex G, "Biological effects at low radiation doses". Much knowledge about the process remains to be learned. Although the concept of sequential, interacting gene mutations as the driving force for tumorigenesis is more firmly established, there is a lack of understanding of the complex interplay between those events and the consequences for cellular behaviour and tissue homeostasis; uncertainty also exists about the contribution made to malignant development of non-mutational (epigenetic) cellular events such as gene silencing and cellular communication changes.

61. Direct evidence on the nature of radiation-associated initiating events in human tumours is sparse, and rapid progress in the area should not be anticipated. By contrast, good progress is being made in resolving early events in radiation-associated tumours in mouse models. Those molecular observations strengthen the view expressed in the UNSCEAR 1993 Report that radiation-induced tumorigenesis will tend to proceed via gene-specific losses; a contribution from early arising epigenetic events should not, however, be discounted.

62. Much information points to the crucial importance of DNA repair and other damage-response functions in tumorigenesis. DNA damage-response functions influence the appearance of initial events in the multi-stage process and reduce the probability that a benign tumour will spontaneously acquire the secondary mutations necessary for full malignant development. Thus, mutations of DNA damage-response genes in tumours play an important role in the spontaneous development of genomic instability.

63. The repair of sometimes complex DNA double-strand lesions is largely error-prone and is an important determinant of dose, dose rate and radiation quality effects in cells. Uncertainties continue to surround the significance to tumorigenesis of adaptive responses to DNA damage; the mechanistic basis of such responses has yet to be well characterized, although associations with the induction of biochemical stress responses seems likely. Recent scientific advances highlight the differences in complexity and reparability between spontaneously arising and radiation-induced DNA lesions. Those data argue against basing judgements concerning low-dose response on comparisons of overall lesion abundance rather than their nature.

64. The research findings on the adaptive responses to radiation in cells and organisms were reviewed in the UNSCEAR 1994 Report, and the typical expression of an adaptive response is described there. The phenomenon has been interpreted as being the result of an initial small (priming) dose activating a repair mechanism that reduces the response to a subsequent larger (challenge) dose. Apparently, the range of priming doses is limited, the time for presenting the challenge dose is critical and the challenge dose needs to be of a reasonable magnitude. The response varies greatly between individual donors of lymphocytes. Nevertheless, the adaptive response has been seen in many systems, including human lymphocytes, a variety of mouse cells and with some chemical agents such as hydrogen peroxide and bleomycin as well as with radiation. However, so far there appears to be no generally reproducible reduction in tumour induction following low-dose irradiation.

65. The basic premises of radiation response are that any radiation interaction with DNA results in damage that if not repaired or if incorrectly repaired may represent an initiating event in the tumorigenesis pathway. The mutation of genes commonly results in modulation of their expression, with loss of gene products (proteins) or alteration in their properties or amounts. The biochemical balance of the cell may then be disrupted, compromising the control of cell signalling or the proliferation and differentiation schedules. In that way, mutated cells, instead of being checked or killed, may be allowed to proceed to clonal growth. Some non-mutational (epigenetic) events or damage may be involved or contribute to those changes. In some cases the genome may be destabilized, allowing further mutations to accumulate, which may promote the progression of tumorigenesis.

66. The judgement as to whether there might be a threshold level of exposure below which biological response does not occur can be guided by mechanistic considerations. Specifically, there is a need to know whether at very low doses the repair processes are more efficient and perhaps enhanced by the adaptive response, preventing any damage to the cellular components. Such a threshold could occur only if repair processes were totally effective in that dose range or if a single track were unable to produce an effect. The absence of consistent indications of significant departures from linearity of tumorigenic response at low doses in cellular endpoints (chromosome aberrations, gene mutation, cell transformation), the activity of well characterized error-prone DNA repair pathways and the evidence on the nature of spontaneous DNA damage in mammalian cells argue against adaptive or other processes that might provide for a dose threshold for radiation effects. The cellular processes such as apoptosis and cellular differentiation that can protect against later phases of tumorigenesis are judged to be efficient but can be bypassed; there is no reason to believe that those defences act differently on spontaneous and radiation-induced tumours or have specific dose dependencies.

67. It may therefore be concluded that, as far as is known, even at low doses radiation may act as a mutational initiator of tumorigenesis and that anti-tumorigenic defences are unlikely to show low-dose dependency. In general, tumorigenic response does not therefore appear to be a complex

function of increasing dose. The simplest representation is a linear relationship, which is consistent with most of the available mechanistic and quantitative data. There may be differences in response for different types of tumour and statistical variations in each data set are inevitable. A departure from linearity is noted for leukaemia data, for which a linear-quadratic function is used. Skin cancer and some cancers induced by alpha emitters may have virtual thresholds. Because of the multi-step nature of the tumorigenesis process, linear or linear-quadratic functions are used for representational purposes only in evaluating possible radiation risks. The actual response may involve multiple and competing processes that cannot yet be separately distinguished.

B. COMBINED EFFECTS

68. Combined exposures to radiation and other physical, chemical or biological agents in the environment are a characteristic of life. The characteristics and effects of combined exposures are reviewed in Annex H, "Combined effects of radiation and other agents". Although both synergistic and antagonistic combined effects are common at high exposures, there is no firm evidence for large deviations from additivity at controlled occupational or environmental exposures. This holds for mechanistic considerations, animal studies and epidemiology-based assessments. Therefore, in spite of the potential importance of combined effects, results from assessments of the effects of single agents on human health are generally deemed applicable to exposure situations involving multiple agents.

69. Deviation from additivity depends on the specificity of the agents for the different steps in the sequence leading to clinical effect. Such effects are, however, only to be expected in cases where both agents are responsible for a large fraction of the total transitions through the sequence. For agents acting independently and through different mechanisms and pathways, simple additivity is predicted.

70. Because exposure to both cigarette smoke and radon is so prevalent, that combined effect is of special importance. Cigarette smoke is a complex mixture of chemical and physical agents and there is still no clear picture of the interaction mechanisms. Epidemiological data clearly indicate that the interaction at intermediate to high exposure levels leads to more-than-additive effects on lung cancer. For example, enhanced radiation risks (more than additive but less than multiplicative) to smokers are evident in the radon miner studies.

71. With the exception of radiation and smoking, there is little indication from epidemiological data for a need to adjust for strong antagonistic or synergistic combined effects. The lack of pertinent data on combined effects does not imply per se that interactions between radiation and other agents do not occur and have no influence on the radiation risk at low doses. Indeed, substances with tumour promoter and/or inhibitor activities are found in the daily diet and cancer risk therefore depends on lifestyle, in particular eating habits. Not only can those agents modify the natural or spontaneous cancer incidence, but they may also modify the carcinogenic potential of radiation. Such modifications would influence the outcome in particular when radiation risks were projected relative to the spontaneous cancer incidence.

72. In general, it can be concluded that genotoxic agents with similar biological and mechanistic behaviour and acting at the same time will interact in a concentration-additive manner (isoadditive). This means that concurrent exposures to ionizing radiation and other DNA-damaging agents with no specific affinity to those DNA sequences which are critically involved in carcinogenesis will generally result in effects not far from isoadditive.

C. CANCER EPIDEMIOLOGY

73. Radiation-associated cancer in humans is studied in population groups that have been exposed to radiation doses such that cancer cases in excess of the normal background incidence may be identified. Estimates of risk may be derived from populations for whom individual doses can be reasonably estimated. Those populations include survivors of the atomic bombings, medically irradiated patients, those occupationally exposed, individuals exposed to radionuclides released into the environment, and people exposed to elevated levels of natural background radiation. Since the Committee's assessment of the risks of radiation-induced cancer in the UNSCEAR 1994 Report, additional important information has become available from epidemiological studies. Those data are summarized in Annex I, "Epidemiological evaluation of radiation-induced cancer".

74. It is now known that radiation can cause cancer in almost any tissue or organ in the body, although some sites are much more prone than others (see paragraph 77). A clearer understanding of physiological modifying factors, such as sex and age, has developed over the last few years. Although differences in the absolute risk of tumour induction with sex are not large and vary with site, for most solid cancers the absolute risk is higher in women than in men. People who were young at the time of radiation exposure have higher relative and absolute risks than older people, but again this varies by site.

75. Further follow-up of radiation-exposed cohorts has demonstrated that excess cancers continue to occur at long times after radiation exposure and, therefore, large uncertainties can arise in the projection of lifetime risks. Data for the Japanese atomic bomb survivors are consistent with a linear or linear-quadratic dose response over a wide range of doses, but quantifying risks at low doses is less certain because of the limitations of statistical precision, potential residual biases or other methodological problems and the possibility of chance findings due to multiple statistical testing. Longer follow-up of cohorts with a wide range of doses, such as the atomic bomb survivors, will provide more essential informa-

tion at low doses, but epidemiology alone will not be able to resolve the issue of whether there are low-dose thresholds. It should be noted, however, that the inability to detect increased risks at very low doses does not mean that those increases in risk do not exist.

76. The studies of the Japanese survivors are particularly important because the cohort includes a large exposed population of both sexes, a wide distribution of doses and the full range of ages. The results of that research provide the primary basis for estimating the risk of radiation-induced cancer. Among the 86,572 individuals in the Life Span Study cohort of survivors of the atomic bombings, there were 7,578 deaths from solid tumours during 1950-1990. Of those cancer deaths, 334 can be attributed to radiation exposure. During the same period, 87 of 249 leukaemia deaths can be attributed to radiation exposure. In 1991, at the time of the latest evaluation, some 48,000 persons (56%) were still living. It is projected that 44% of the population will still be living in 2000.

77. The Life Span Study cancer incidence and mortality data are broadly similar, demonstrating statistically significant effects of radiation for all solid tumours as a group, as well as for cancers of the stomach, colon, liver, lung, breast, ovary and bladder. The incidence data also provide evidence of excess radiation risks for thyroid cancer and non-melanoma skin cancers. Statistically significant risks were not seen in either the incidence or the mortality data for cancers of the rectum, gall bladder, pancreas, larynx, uterine cervix, uterine corpus, prostate gland and kidney or renal pelvis. An association with radiation exposure is noted for most types of leukaemia, but not for lymphoma or multiple myeloma.

78. The numbers of solid tumours associated with radiation exposure are not sufficient to permit detailed analysis of the dose response for many specific sites or types of cancer. For all solid tumours combined, the slope of the dose-response curve is linear up to about 3 Sv, but the dose-response curve for leukaemia is best described by a linear-quadratic function. Statistically significant risks for cancer in the Life Span Study are seen at organ doses above about 100 mSv.

79. Studies of populations exposed to medical, occupational or environmental radiation provide information on issues that cannot be addressed by the atomic bomb survivor data, such as the effects of chronic low doses, alpha doses to the lung from radon, highly fractionated doses and variability among populations. For some cancer sites, including leukaemia, breast, thyroid gland, bone and liver, very useful results come from investigations other than the Life Span Study. Risk estimates derived from those studies generally agree well with those from the Life Span Study.

80. Large studies of occupationally exposed persons are also contributing valuable data on low-dose effects. A combined analysis of data for a large number of nuclear workers indicates that the risk of leukaemia increases with increasing dose. However, the statistical precision of such studies is still low in comparison with the results at high-dose rate from the atomic bomb survivors. As a result, it is difficult to arrive at a definitive conclusion on the effects of dose rate on cancer risks, in particular since those effects may differ among cancer types. However, the conclusions reached in the UNSCEAR 1993 Report, based on both epidemiological and experimental evidence that suggested a reduction factor of less than 3 when extrapolating to low doses or low-dose rates, still appear to be reasonable in general.

81. Information on the effects of internal doses, from both low- and high- linear energy transfer (LET) radiation, has increased since the time of the UNSCEAR 1994 Report. In particular, an elevated risk of thyroid cancer in parts of Belarus, the Russian Federation and Ukraine contaminated as a result of the Chernobyl accident shows a link with radioactive iodine exposure during childhood. However, risk estimation associated with those findings is complicated by difficulties in dose estimation and in quantifying the effect of screening for the disease. Other studies in the former Soviet Union have provided further information on internal doses, for example, an increased risk of lung cancer among workers at the Mayak plant. Leukaemia was elevated in the population living near the Techa River. However, the different sources of radiation exposure (both external and internal) and, in the case of the Techa River studies, the potential effects of migration, affect the quantification of risks. Results from several case-control studies of lung cancer and indoor radon have been published in recent years that, in combination, are consistent with extrapolations from data on radon-exposed miners, although the statistical uncertainties in those findings are still large.

82. Particular attention has been paid in Annex I to risks for specific cancer sites. Again, the new information that has become available in recent years has helped in the examination of some risks. However, for some cancer sites there remain problems in characterizing risks, owing to the low statistical precision associated with moderate or small excess numbers of cases. This can limit, for example, the ability to estimate trends in risk in relation to factors such as age at exposure, time since exposure and gender. An exception is breast cancer, where a comparison of data on the Japanese atomic bomb survivors and women with medical exposures in North America points to an absolute transfer of risks between populations. There are some cancer sites for which there is little evidence for an association with radiation (e.g. non-Hodgkin's lymphoma, Hodgkin's disease and multiple myeloma). While the evaluations for the lymphomas are affected in part by the small numbers of cases in several studies, they should be contrasted with the evaluations for leukaemia (excluding chronic lymphocytic leukaemia), which, while also a rare disease, has clearly been related to radiation in many populations.

83. Lifetime risk estimates are sensitive to variations in background tumour rates and the variability can lead to differences that are comparable to differences associated with the transport method across populations or the method of risk projection. The variability in such projections

highlights the difficulty of choosing a single value to represent the lifetime risk of radiation-induced cancer. Furthermore, uncertainties in estimates of risk for specific types of cancer are generally greater than for all cancers combined.

84. Based on the available epidemiological data, the Committee has derived risk estimates for radiation-induced cancer. For a population of all ages and both genders with an acute dose of 1 Sv (low-LET), it is suggested that lifetime risk estimates for solid cancer mortality might be taken as 9% for men and 13% for women. The uncertainties in the estimates may be a factor of about 2, higher or lower. The estimates could be reduced by 50% for chronic exposures, as discussed in the UNSCEAR 1993 Report, again with an uncertainty factor of 2, higher or lower. Solid cancer incidence risks can be taken as being roughly twice those for mortality. Lifetime solid cancer risks estimates for those exposed as children might be twice the estimates for a population exposed at all ages. However, continued follow-up in studies of such groups will be important in determining lifetime risks. The experience of the Japanese atomic bomb survivors provides compelling evidence for linearity in estimating excess risks of solid cancers; therefore, as a first approximation, linear extrapolation of the estimates at 1 Sv could be used for estimating solid cancer risks at lower doses.

85. The estimates of lifetime risks for leukaemia are less variable. The lifetime risk of death from leukaemia may be taken as 1%, for either gender, following an acute dose of 1 Sv. The uncertainty in the estimate may be about a factor of 2, higher or lower. In view of non-linearity in the dose response, decreasing the dose tenfold, from 1 Sv to 0.1 Sv, will result in a 20-fold decrease in the lifetime risk if the dose is acute. The risks of solid cancer and leukaemia are broadly similar to those estimated in the UNSCEAR 1994 Report.

86. One radiation-associated cancer of particular importance in children is cancer of the thyroid gland. There is strong evidence that the risk of thyroid cancer decreases with increasing age at exposure, so that the risk in children under 15 years of age is substantially larger than in adults. Among children, those aged 0-5 years are five times more sensitive than those aged 10-14 years. In view of that sensitivity, it is not surprising that large increases in thyroid cancer incidence have been observed in children in Belarus, the Russian Federation and Ukraine following the Chernobyl accident in 1986. The incidence rate of thyroid cancer in children from regions of those countries was ten times higher in 1991-1994 than in the preceding five years. About 1,800 cases of childhood thyroid cancer had occurred as at 1998. The topic is reviewed extensively in Annex J of this report, "Exposures and effects of the Chernobyl accident".

87. Cancer may be induced by prenatal exposure. In humans, the induction of childhood cancers, leukaemia and solid cancers as a result of exposure to x rays was first reported in 1958, when the Oxford Survey established an increased incidence of childhood tumours in the first 15 years of life for those exposed to x rays *in utero* compared with those who were not exposed. The attribution of that increase to radiation exposure has been criticized by some on the grounds that the exposed women may have had medical or other conditions that were responsible for the increased cancer rates. Support for the causal role of radiation is found in some other studies, and the risk, if genuine, was estimated to be about 5 % per Sv. No such effects were observed in survivors of the atomic bombings irradiated *in utero*.

88. Risks of induced cancer expressed in adulthood among those exposed *in utero* are more difficult to evaluate. Nevertheless, the fact that relative risks increase with decreasing age at exposure among the survivors of the atomic bombings causes concern about a potentially greater sensitivity to cancer induction for those exposed *in utero* than for those exposed at young ages. The atomic bomb survivors exposed *in utero* are now 55 years old. Thus it is especially important to evaluate their cancer risk experience later in life.

III. THE CHERNOBYL ACCIDENT

89. The Committee has given special attention to the accident at the Chernobyl nuclear reactor that occurred on 26 April 1986. It was the most serious accident ever to occur in the nuclear power industry. The reactor was destroyed in the accident, considerable amounts of radioactive materials were released to the environment and many workers were exposed to high doses of radiation that had serious, even fatal, health consequences (see below). Among the residents of Belarus, the Russian Federation and Ukraine, well over a thousand cases of thyroid cancer (about 1,800) have been reported in children. Notwithstanding problems associated with screening, those cancers were most likely caused by radiation exposures received at the time of the accident. Many other health problems have been noted in the populations that are less likely to be related to radiation exposures. From a scientific point of view, there is a need to evaluate and understand the technical causes and effects of the accident. From a human point of view, there is also an obligation to provide an objective analysis of the health consequences of the accident for the people involved. The Committee has prepared a further assessment of the accident with both objectives in mind.

90. Soon after the accident, the deposition of dispersed radionuclides and the exposures that resulted were measured and evaluated throughout the region affected. The Committee made use of those data to evaluate the average individual and

population doses for the various regions and countries and for the northern hemisphere as a whole. The results were presented in the UNSCEAR 1988 Report, Annex D, "Exposures from the Chernobyl accident". The experience gained in treating the immediate radiation injuries of workers and firefighters involved in controlling the accident were also reviewed in the Appendix to Annex G, "Early effects in man of high doses of radiation", of the same report.

91. Evaluating the exposures received by the people who were evacuated or who still reside in the areas most affected by the accident has required much time and effort. The initial measurements must be supplemented by information on such things as the location and diet of the people in each settlement. The accumulation of data on late health effects has also required further time. Only now, some 15 years after the accident, can an initial assessment of the local exposures and effects of the accident be made. The detailed results of the Committee's assessment are presented in Annex J of this report, "Exposures and effects of the Chernobyl accident".

A. RELEASE OF RADIONUCLIDES

92. The accident at the Chernobyl reactor happened during an experimental test of the electrical control system as the reactor was being shut down for routine maintenance. The operators, in violation of safety regulations, had switched off important control systems and allowed the reactor to reach unstable, low-power conditions. A sudden power surge caused a steam explosion that ruptured the reactor vessel, allowing further violent fuel-steam interactions that destroyed the reactor core and severely damaged the reactor building.

93. It is noteworthy that an earlier accident in 1979 at the Three Mile Island reactor in the United States of America also resulted in serious damage to the reactor core but without a steam explosion. In that case, however, the containment building surrounding the reactor prevented the release of all but trace amounts of radioactive gases. The Chernobyl reactor lacked the containment feature. Following the explosions, an intense graphite fire burned for 10 days. Under those conditions, large releases of radioactive materials took place.

94. The radioactive gases and particles released in the accident were initially carried by the wind in westerly and northerly directions. On subsequent days, the winds came from all directions. The deposition of radionuclides was governed primarily by precipitation occurring during the passage of the radioactive cloud, leading to a complex and variable exposure pattern throughout the affected region.

B. EXPOSURE OF INDIVIDUALS

95. The radionuclides released from the reactor that caused exposure of individuals were mainly iodine-131, caesium-134 and caesium-137. Iodine-131 has a short radioactive half-life (eight days), but it can be transferred to humans relatively rapidly from the air and through milk and leafy vegetables. Iodine becomes localized in the thyroid gland. For reasons related to the intake of those foods by infants and children, as well as the size of their thyroid glands and their metabolism, the radiation doses are usually higher for them than for adults.

96. The isotopes of caesium have relatively longer half-lives (caesium-134 has a half-life of 2 years while that of caesium-137 is 30 years). These radionuclides cause longer-term exposures through the ingestion pathway and through external exposure from their deposition on the ground. Many other radionuclides were associated with the accident, which have also been considered in the exposure assessments.

97. Average doses to those persons most affected by the accident were about 100 mSv for 240,000 recovery operation workers, 30 mSv for 116,000 evacuated persons and 10 mSv during the first decade after the accident to those who continued to reside in contaminated areas. Maximum values of the dose may be an order of magnitude higher. Outside Belarus, the Russian Federation and Ukraine, other European countries were affected by the accident. Doses there were at most 1 mSv in the first year after the accident with progressively decreasing doses in subsequent years. The dose over a lifetime was estimated to be 2-5 times the first-year dose. These doses are comparable to an annual dose from natural background radiation and are, therefore, of little radiological significance.

98. The exposures were much higher for those involved in mitigating the effects of the accident and those who resided nearby. Those exposures are reviewed in great detail in the assessment of the Committee.

C. HEALTH EFFECTS

99. The Chernobyl accident caused many severe radiation effects almost immediately. Of 600 workers present on the site during the early morning of 26 April 1986, 134 received high doses (0.7-13.4 Gy) and suffered from radiation sickness. Of these, 28 died in the first three months and another 2 soon afterwards. In addition, during 1986 and 1987, about 200,000 recovery operation workers received doses of between 0.01 Gy and 0.5 Gy. That cohort is at potential risk of late consequences such as cancer and other diseases and their health will be followed closely.

100. The Chernobyl accident also resulted in widespread radioactive contamination in areas of Belarus, the Russian Federation and Ukraine inhabited by several million people. In addition to causing radiation exposure, the accident caused long-term changes in the lives of the people living in the contaminated districts, since the measures intended to limit radiation doses included resettlement, changes in food supplies and restrictions on the activities of individuals and families. Later on, those changes were accompanied by the major economic, social, and political changes that took place when the former Soviet Union broke up.

101. For the last 14 years, attention has been focused on investigating the association between exposure caused by radionuclides released in the Chernobyl accident and late effects, in particular thyroid cancer in children. A majority of the studies completed to date are of the descriptive type, in which average population exposures are correlated with the average rates of cancer incidence over specific periods of time. As long as individual dosimetry is not available, it is difficult to determine whether the effects are radiation-related and it is also impossible to make reliable quantitative estimates of risk. The reconstruction of individual doses is a key element for future research on radiation-associated cancers related to the Chernobyl accident.

102. The number of thyroid cancers (about 1,800) in individuals exposed in childhood, in particular in the severely contaminated areas of the three affected countries, is considerably greater than expected based on previous knowledge. The high incidence and the short induction period are unusual. Other factors may be influencing the risk. If the current trend continues, additional thyroid cancers can be expected to occur, especially in those who were exposed at young ages.

103. Apart from the increase in thyroid cancer after childhood exposure, no increases in overall cancer incidence or mortality have been observed that could be attributed to ionizing radiation. The risk of leukaemia, one of the main concerns (leukaemia is the first cancer to appear after radiation exposure owing to its short latency time of 2-10 years), does not appear to be elevated, even among the recovery operation workers. Neither is there any proof of other non-malignant disorders that are related to ionizing radiation. However, there were widespread psychological reactions to the accident, which were due to fear of the radiation, not to the actual radiation doses.

104. There is a tendency to attribute increases in the rates of all cancers over time to the Chernobyl accident, but it should be noted that increases were also observed before the accident in the affected areas. Moreover, a general increase in mortality has been reported in recent years in most areas of the former Soviet Union, and this must be taken into account when interpreting the results of Chernobyl-related studies.

105. The present understanding of the late effects of protracted exposure to ionizing radiation is limited, since the dose-response assessments rely heavily on studies of exposure to high doses and animal experiments; extrapolations are needed, which always involves uncertainty. The Chernobyl accident might shed light on the late effects of protracted exposure, but given the low doses received by the majority of exposed individuals, any increase in cancer incidence or mortality will be difficult to detect in epidemiological studies. One future challenge will be to develop individual dose estimates including estimates of uncertainty, and to determine the effects of doses accumulated over a long period of time.

Notes

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 General Assembly increased the membership of the Committee to a maximum of 21 members and invited China to become a member.

2 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). These documents are referred to as the 1958, 1962, 1964, 1966, 1969, 1972, 1977, 1982, 1986, 1988, 1993, 1994 and 1996 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, No. E.94.IX.11 and E.96.IX.3, respectively).

Appendix I

Members of national delegations attending the forty-fourth to forty-ninth sessions

Argentina	D. Beninson (Representative), E. D'Amato, D. Cancio
Australia	P. A. Burns (Representative), K. H. Lokan (Representative), J. Loy, D. I. Macnab
Belgium	J. R. Maisin (Representative), A. Debauche, R. Kirchmann, H. P. Leenhouts, J. Lembrechts, K. Sankaranarayanan, P. Smeesters, J. van Dam, H. Vanmarcke, A. Wambersie
Brazil	J. L. Lipsztein (Representative), D. Melo, A. T. Ramalho, E. R. Rochedo
Canada	R. M. Chatterjee (Representative), D. B. Chambers, R. J. Cornett, N. E. Gentner (Representative), R. V. Osborne (Representative), S. Vlahovich (Representative)
China	Z. Pan (Representative), N. Gu, F. He, Q. He, J. Ma, B. Mao, K. Li, P. Liu, Y. Song, Z. Tao, K. Wei, B. Xiu, H. Yang, L. Zhang, Y. Zhao, J. Zhou, B. Zhu
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Appendix II

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ANNEX A

Dose assessment methodologies

CONTENTS

INTRODUCTION

1. The estimation of exposures of human populations from the various sources of radiation is an important and continuing goal of the Committee. In its previous assessments, the Committee took many different approaches to dose estimation, depending mainly on the availability of data. These methods have been documented in the UNSCEAR reports. To ensure that the methods are relevant for continued use, the assumptions and parameters must be reviewed from time to time and, if necessary, updated for improved accuracy. The objective of this Annex is to provide such a review of dose estimation procedures.

2. The initial work of the Committee involved evaluating the doses from natural background sources and from the testing of nuclear weapons in the atmosphere. In each case, the starting point of the calculations was where the fewest steps or assumptions would be needed, for example, the concentrations of radionuclides in the body or the deposition of radionuclides on the ground. To evaluate the exposures from nuclear power production, generic models had to be used to estimate the dispersion of radionuclides in the environment, the transfer to humans and the doses from various pathways, since the concentrations or depositions were not measurable at the point of interest. To evaluate the exposures resulting from the Chernobyl accident, some of the dose estimation procedures were modified to account for seasonal and other features indicated by available measurements.

3. In most cases, the Committee has been interested in evaluating the average annual doses from the naturally occurring levels of radionuclides in the environment and from the releases due to man-made practices or events. There has been little need for detailed, time-dependent dose modelling; the use of transfer coefficients or equilibrium modelling has been adequate for purposes of the Committee. Data compilations have been generalized to allow widespread use in both time and space. Although projections were needed to obtain committed doses, there has been little emphasis on prognostic modelling. In general, data-based methods of assessment with more direct and simpler dose estimation procedures have provided results of reliable accuracy and allowed scientists throughout the world to understand and apply or adapt these same methods. This historical viewpoint is significant and important to understand the evaluations of the Committee. In specific circumstances, more theoretical or more detailed models might have been more appropriately considered, but these have generally not been used by the Committee, nor will they be described or used in this Annex.

4. The Committee previously summarized its dose estimation procedures in Annex A, “Concepts and quantities in the assessment of human exposures”, of the UNSCEAR 1977 Report [U7] and in Annex A, “Dose assessment models”, of the UNSCEAR 1982 Report [U6]. These reviews are extended in this Annex with consideration of dose estimation procedures used in all earlier assessments of the Committee. The selection of models and the values of the parameters have been adjusted, based on best available estimates.

5. The procedures and models developed and used by the Committee are believed to be reasonably accurate in general application. They are largely based on empirical evaluations of available measurements. In the widest sense, the estimates of the average doses to the global population from radiation sources are certainly well within the wide

variations that are known to exist. It is clear, however, that more regionally appropriate values of environmental conditions or of human habits apply in specific circumstances. Thus, the calculational procedures described here should be used in other applications only with caution, and site-specific data should be used where appropriate.

I. GENERAL CONSIDERATIONS FOR DOSE ASSESSMENTS

A. DOSIMETRIC QUANTITIES

1. Definitions

6. For radiation assessment purposes, a number of specialized quantities are used. A historical review of the quantities used by the Committee was presented in the UNSCEAR 1988 Report [U4]. The Committee uses the system of radiation quantities and units adopted in 1980 by the International Commission on Radiation Units and Measurements (ICRU) [I8, I12] and the revised terminology and definitions proposed in 1990 by the International Commission on Radiological Protection (ICRP) [I1].

7. For assessments by the Committee, the fundamental dosimetric quantity used is the absorbed dose, D, averaged over a tissue or organ; its unit is joule per kilogram, which is given the special name gray (Gy). The relationship of this quantity to the risk of biological effect is described by the weighted dose quantities. Values of weighting factors have been recommended by ICRP for the various types and energies of radiation incident on the body or emitted from within the body and for selected tissues and organs [I1]. Equivalent dose, H_T, is the averaged absorbed dose in tissue or organ T, modified by the radiation weighting factor, w_R:

$$H_T = \sum_R w_R D_{T,R} \qquad (1)$$

where $D_{T,R}$ is the mean absorbed dose in tissue or organ T due to radiation R. The unit of equivalent dose is joule per kilogram, and it is given the special name sievert (Sv). Values of w_R are given in Table 1.

8. Effective dose, E, is the sum of the weighted equivalent doses in all the tissues and organs of the body. It is calculated from the following expression, where w_T is the weighting factor for tissue T:

$$E = \sum_T w_T \sum_R w_R D_{T,R} \qquad (2)$$

Effective dose has the unit joule per kilogram, which is given the name sievert (Sv). ICRP has selected values of w_T to assess health detriment arising from the irradiation of various organs and tissues. The recommended values of w_T are given in Table 2. The values have been selected for a reference population of equal numbers of both sexes and a wide range of ages. They apply to workers, to the general public and to either sex.

9. The above definition of effective dose replaces a previous similar definition of effective dose equivalent, H_E:

$$H_E = \sum_T w_T(1977) \sum_R w_R D_{T,R} \qquad (3)$$

which was promulgated by ICRP in 1977 [I11]. The difference between H_E and E is in the values of the weighting factors, w_T. In equation (3) this is noted by appending (1977) to the w_T expression. Values of $w_T(1977)$ are also indicated in Table 2. Normally, this now outdated concept would not be used by the Committee, but some very extensive calculations of external dose coefficients have been performed and reported as values of H_E rather than E, and there is no unambiguous way to convert from one value to another without access to the original calculations. It is presumed that eventually these calculations will be repeated so that values of E can be used in those few circumstances where it is not now possible. For high-energy gamma radiation the numerical values of E and H_E should be approximately the same. However, for low-energy gamma radiation, bremsstrahlung, and electrons, the dose to the skin is typically much higher than the dose to any other organ, and the skin was specifically excluded from consideration in H_E. To simulate the value of E where complete recalculation of E from H_E is not possible, the value of 0.01 H_{skin} has been added to H_E. This practice of adding a weighted component of skin dose to H_E was suggested by ICRP [I14] in 1978 and was first used by the Committee in the UNSCEAR 1982 Report [U6] to calculate doses from fission noble gases released from nuclear reactors.

10. The term exposure is often used in the general sense of being exposed to a radiation source, inferring that a dose is received, but it also has a more specific definition. Exposure is the total electrical charge of ions of one sign produced in air by electrons liberated by x or gamma rays per unit mass of irradiated air at NTP. The unit of exposure is coulomb per kilogram. An old unit, the roentgen, R, is still used, as noted, for example, in reporting after the Chernobyl accident. One roentgen is equal to $2.58\ 10^{-4}$ C kg^{-1}. In this sense, the term exposure applies to ionization of air by x or gamma rays, but the more common usage is also prevalent. Another dosimetric quantity is the kerma, which is the initial energy of charged particles liberated by uncharged particles in a unit mass of material. The unit is joule per kilogram, given the name gray (Gy). Under the assumption that charged particle equilibrium exists within the

volume of material, the kerma and absorbed dose may be assumed to be equivalent. This assumption is used by the Committee in most circumstances in specifying absorbed dose rates in air or tissue.

11. When radionuclides are released to the environment, they persist until they are lost through radioactive decay, causing radiation exposures into the future. To compare doses delivered over different time periods, the Committee introduced the concept of the dose commitment. The dose commitment, $H_{c,T}$ or E_c, is defined as the time integral of the average individual dose rate (per caput dose rate) delivered as a result of a specific practice:

$$H_{c,T} = \int_0^\infty \dot{H}_T dt \qquad \text{or} \qquad E_c = \int_0^\infty \dot{E}(t) dt \tag{4}$$

The integral is taken over infinite time to account for exposures occurring during all future time and may thus involve the average individual dose rates over generations. The dose commitment from one year of a practice is numerically equal to the equilibrium dose rate, if the practice continues indefinitely at constant rate. If the integration is carried out only to a specified time, this is then termed a truncated dose commitment.

12. When prolonged exposure to a single individual from a single intake of a radionuclide is being considered, committed dose quantities are used. The time distributions of the absorbed dose rates vary with the radionuclides, their form, mode of intake, and biokinetic behaviour. The committed equivalent dose, $H_T(\tau)$, is defined as the time integral of the equivalent dose rate, where τ is the integration time in years:

$$H_T(\tau) = \int_t^{t_0+\tau} \dot{H}_T(t) dt \tag{5}$$

The value of τ is taken to be 50 years for adults and from time of intake to age 70 years for children. The committed effective dose, $E(\tau)$, is the sum of the committed equivalent doses to tissues and organs multiplied by the appropriate tissue weighting factors, w_T. In general, the Committee considers doses to adults; doses to children are considered only when such doses are significantly different. ICRP has developed age-dependent models for the respiratory and gastrointestinal tract and for the systemic biokinetic behaviour of radionuclides that are of importance in the environment. These models have been used to compute values of committed effective dose per unit intake by members of the public by inhalation and ingestion. These values are compiled in ICRP publications [I2, I3, I4, I5], and general use of these values is made by the Committee.

13. Collective dose quantities have also been used by the Committee. These are aggregate quantities of dose and population size. The collective equivalent dose, S_T, is the average equivalent dose in an exposed group of individuals multiplied by the number of individuals in each group:

$$S_T = \sum_i \overline{H}_{T,i} N_i \tag{6}$$

where N_i is the number of individuals in population subgroup i receiving mean organ equivalent dose $H_{T,i}$. The collective effective dose, S, is defined in a similar manner. The population and the time period over which the dose is determined should be specified. The collective dose commitment may become rather uncertain if applied to very long time periods in which future environmental conditions and the populations affected cannot be reasonably anticipated.

2. Age groupings

14. In many instances, the effective doses in populations have been estimated by the Committee for the adult individual. Data on concentrations of radionuclides in tissues have not always been widely available for other age groups. In some cases, the uncertainties have been as great as the possible differences. For certain radionuclides and pathways, however, the differences may justify separate dose estimates. This is particularly true for ^{131}I. The availability of dose per unit intake estimates for other age groups means that calculated dose estimates can be derived from measured concentrations in foods, and more extensive reporting of age-specific results can be expected in the future.

15. Earlier estimates of doses from fallout ^{131}I were made for infants, using the age of 6 months as representative of the 0–1 year age group [U7, U8]. For releases of ^{131}I from nuclear reactors, parameters were given in the UNSCEAR 1977 Report [U7] for the ages 6 months, 4 years, 14 years and adult. For assessment of exposures from the Chernobyl accident, dose estimates for ^{131}I were made for 1-year-old infants and adults [U4]. In the UNSCEAR 1993 Report [U3], food consumption amounts were indicated for infants, children and adults. In that report age-weighted annual intakes of naturally occurring radionuclides were then derived, assuming the fractional distribution of adults, children and infants in the population to be 0.65, 0.3, and 0.05, respectively. An age-independent dose per unit intake (the adult value) was applied [U3]. Age-dependent dose coefficients are now available from ICRP, and the number of age groups considered could be expanded to six: 3 months (from 0 to 1 years), 1 year (from 1 year to 2 years), 5 years (>2 years to 7 years), 10 years (>7 years to 12 years), 15 years (>12 years to 17 years), and adult. For most purposes, the Committee will consider the age categories of infants, children, and adults and use the available dose coefficients corresponding to 1–2 years, 8–12 years, and >17 years, respectively, for these categories. The fractional distribution of the population within these categories is that mentioned above, namely, 0.05, 0.3, and 0.65 for infants, children and adults, respectively.

B. ENVIRONMENTAL BEHAVIOUR OF RADIONUCLIDES

1. Transfer processes

16. Radionuclides are generally released in trace quantities to the environment. They are then physically transported in the air or water media in which they are located. The measurements of radionuclide transfers from past releases have been used to study and infer large-scale atmospheric and hydrological movements on the earth. The fallout radionuclides ^{90}Sr and ^{137}Cs have been used to infer material removal or renewal times (residence times) in environmental regions. Tritium is a tracer for the world hydrological cycle and ^{14}C for the global carbon cycle. The specific removal or transfer processes of the various exposure pathways have been extensively studied.

17. Radioactive materials, either particles or gases, may be transported great distances by local and large-scale air movements. The time periods that the materials remain airborne depend on the latitude, time of year and height of injection into the atmosphere. The depletion processes include gravitational settlement and dry impaction, incorporation into rain drops and washout by falling precipitation. The physical and chemical characteristics of the materials themselves, such as particle size and chemical and physical forms, may influence the removal rates.

18. The predominant features of large-scale mixing processes and air movements in the atmosphere were presented in the UNSCEAR 1982 Report [U6] in connection with discussion of exposures from nuclear explosions. They were used to describe the occurrence of fallout. The measured deposition of ^{90}Sr could, however, be used as a starting point for the dose assessment, obviating the need to evaluate the deposition from the uncertain input amounts. With improved estimates recently available of the input of fission radionuclides to the atmosphere from nuclear tests, quantitative aspects of the general model can be pursued with seasonal values of residence times assigned to the various compartmental regions and latitudinal deposition estimated. This exercise is discussed in Annex C, "*Exposures to the public from man-made sources of radiation*".

19. Releases of radionuclides from nuclear fuel cycle installations occur at ground level or through stacks of assumed representative heights of 30 or 100 m. The long-term, sector-averaged Gaussian plume model can be used to calculate air concentration for limited distances following airborne releases. Estimates can be obtained directly from the model or from a simple analytical expression that gives a good fit to the model results. The air concentration at one kilometre per unit release is typically 5 10^{-7} s m^{-3} and decreases as a result of further dispersion at a rate inversely proportional to distance, expressed in kilometres, raised to the power 1.2–1.4. Derivation of these quantities is discussed in Section I.B.3. Integration to 50 or 100 km defines the local exposures. Further integration to a distance of 2,000 km defines the continental or regional component of exposure. Most particles from near-surface releases are deposited within this distance. Only fine aerosols and gases may become further dispersed in the troposphere.

20. Global modelling of atmospheric releases will be described with respect to the specific radionuclides. Mixing occurs first within the latitude band, then within the hemisphere. Gradual interhemispheric exchange occurs for gases such as ^{85}Kr, for which removal processes are minimal. Tritium and ^{14}C enter the global cycles of the respective elements.

21. Radioactive material released to the aquatic environment is transported and dispersed by advective and turbulent processes occurring in the water body. Interactions of radionuclides with suspended matter and sediments may remove radionuclides from the solution. Methods for modelling hydrological transport have been developed and applied, usually for specific categories of water bodies: lakes, rivers, estuaries, coastal seas and oceans.

22. UNSCEAR has needed hydrological transport estimates to evaluate the exposures from releases of radionuclides from nuclear fuel cycle installations. For fuel reprocessing plants, use has been made of dispersion estimates surrounding the plants at Sellafield and La Hague. In the general case for reactor releases, the Committee made use of relationships between water volumes, water usage and potential intake to estimate collective doses. The water uses considered included drinking water, fish and seafood production and irrigation. Some minor pathways might be involved in the local regions, such as immersion and exposure to shoreline contaminants. Some general considerations with regard to aquatic models and suggestions about which models to use have been published, e.g. [S2]. Details of the procedures used by UNSCEAR will be presented later in connection with ingestion exposures.

2. Parameters for dose estimation

23. The basic parameters used in models to describe environmental behaviour and transport of radionuclides and to make dosimetric calculations are transfer coefficients, P_{ij}. These describe the relationships of integrated concentrations or dose in successive environmental compartments, e.g. movement from compartment i to compartment j. The pathways of transfer of radionuclides through the environment commonly evaluated in UNSCEAR dose assessments are illustrated in Figure I along with designations of the transfer coefficients. As an example, P_{34} is the time-integrated activity concentration of a radionuclide in the body divided by the time-integrated concentration of the same radionuclide in the diet. This methodology for deriving relationships between measured quantities has been used by the Committee since 1962.

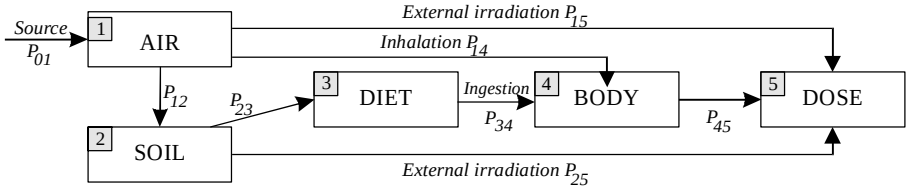

Figure I. Terrestrial pathways of transfer of radionuclides and dose to humans.

24. For a particular environmental transfer pathway, the amount of radionuclide released to the environment multiplied by the intervening transfer coefficients gives an estimate of the resulting effective dose. If measurement results are available at any point in the chain, the calculation may begin at that point. This minimizes the uncertainties that may exist in determining transfer coefficients for earlier steps in the transfer pathway. Thus, assessments of dose derived by the Committee have started with integrated concentrations of radionuclides in air, deposition densities, measured concentrations in foods or body burdens.

25. The measurements used to evaluate transfer coefficients have been made over a number of years by research and monitoring organizations in many locations. The transfer coefficients derived for estimation of effective doses from atmospheric nuclear testing were summarized in the UNSCEAR 1993 Report [U3] for a long listing of radionuclides for the pathways of external irradiation, inhalation and ingestion. The many measurement results acquired following the Chernobyl accident have shown that more seasonal or locally characteristic conditions should be taken into account in evaluating exposures from specific single releases of radioactive materials. Several programmes to compare results and validate models were instigated following the Chernobyl accident. Those activities are contributing results useful for deriving specific values for many transfer coefficients, e.g. [I16, I17].

26. Tritium and ^{14}C are modelled differently than other radionuclides, since they are mobile in the environment and are readily incorporated into living organisms. The transfer of tritium and ^{14}C is not modelled using transfer parameters but by a specific-activity approach. For tritium, it is assumed that the tritium to hydrogen atom ratio in the various environmental compartments is simply proportional to the ratio in moisture in air. For carbon, the ^{14}C activity per gram carbon in all compartments is assumed to be the same as that in air.

27. The specific methods used by the Committee to estimate doses to humans caused by releases of radioactive materials to the environment are described in the following Chapters. The rationale for the selection of the various parameters is presented, so that it will be clear when alternative selections might be desirable for specific local conditions. The methods are intended to be widely applicable, and since they are largely empirically based, they should provide realistic estimates of doses in most general circumstances of release of radionuclides.

3. Atmospheric dispersion from a near-surface release

28. Radionuclide concentrations in the environment downwind of an isolated source such as a nuclear reactor are usually undetectable at distances greater than a few kilometres. In such cases, the air concentrations needed as the starting point for dose assessments to the public must be estimated using a mathematical model.

29. Average air concentrations close to a specific source are traditionally calculated using the long-term sector-averaged Gaussian plume model [I15]. In this model, the plume is assumed to spread uniformly across a sector subtended by an angle $\Delta\theta$ (usually chosen to be 30°). Air concentrations at a given distance downwind are calculated for each of six atmospheric stability classes using average values of wind speed, inversion height and vertical dispersion parameter for each class. The long-term mean concentration is found by summing over classes, taking into account the frequency of occurrence of each class and the frequency with which the wind blows towards the site of interest. The model is able to account for reductions in air concentration due to wet and dry deposition. A general discussion of the processes governing atmospheric dispersion was presented in the UNSCEAR 1982 Report [U6].

30. The mathematical statement of the long-term sector-averaged Gaussian plume model is as follows:

$$C_{a,j} = \left(\frac{2}{\pi}\right)^{1/2} \frac{f_j Q D_w}{x \Delta\theta} \sum_{i=1}^{6} \frac{f_i F(\sigma_{z,i}, H, h_i) \exp(-\lambda x u_i^{-1}) D_{d,i}}{(u_i \sigma_{z,i})} \quad (7)$$

where $C_{a,j}$ is the long-term average air concentration (Bq m^{-3}) in sector j; f_j is the frequency with which the wind blows into sector j; Q is the release rate (Bq s^{-1}); x is the downwind distance (m); $\Delta\theta$ is the sector width (radians); f_i is the frequency of occurrence of stability class i; $F(\sigma_{zi},H,h_i)$ is the vertical shape function; $\sigma_{z,i}$ is the vertical dispersion parameter for stability class i (m); H is the effective release height (m); h_i is the mixed layer height for stability class i (m); λ is the radioactive decay constant for the radionuclide in question (s^{-1}); $D_{d,i}$ is the depletion factor for dry deposition; D_w is the depletion factor for wet

deposition; and u_i is the average wind speed for stability class i at the release height (m s^{-1}).

31. For ground-level concentrations, the vertical shape function is given by

$$F(\sigma_{z,i}, H, h_i) = \sum_{n=-\infty}^{\infty} \exp\left[-\frac{(H+2n\,h_i)^2}{2\sigma_{z,i}^2}\right] \qquad (8)$$

which accounts for reflection from the ground and from an elevated inversion through the method of virtual sources. The summation index n in equation (8) represents the number of reflections that the plume has undergone. The summation converges slowly in some applications. To simplify the calculation, Yamartino [Y1] proposed approximations as follows: for $\sigma_{z,i} / h_i \leq 0.63$, truncate equation (8) at n = 0, ± 1; for $0.63 < \sigma_{z,i}/h_i \leq 1.08$, $F(\sigma_{z,i}, H,h_i) = (2\pi)^{½}\, \sigma_{z,i}/h_i\, (1 - k^2)[1 + k^2 + 2k \cos(\pi H/h_i)]$ where $k = \exp[-½\, (\pi\, \sigma_{z,i}/h_i)^2]$; for $\sigma_{z,i}/h_i > 1.08$, $F(\sigma_{z,i}, H,h_i) = (2\pi)^{½}\, \sigma_{z,i}/h_i$. These approximations result in minimal error in evaluation of equation (8).

32. Plume depletion due to dry deposition is normally treated using the source depletion method, in which case the depletion factor takes the form

$$D_{d,i} = \exp\left[-\alpha_i \int_0^x \frac{\exp\left(-\frac{H^2}{2\sigma_{z,i}^2(x)}\right)}{\sigma_{z,i}(x)}\, dx\right] \qquad (9)$$

where $\alpha_i = (2/\pi)^{½}\, v_d/u_i$ and v_d is the dry deposition velocity (m s^{-1}). The depletion factor for wet deposition is given by $D_w = \exp(-\Lambda t_s)$, where Λ is the washout coefficient (s^{-1}) and t_s (s) is the time over which precipitation occurs during the travel of the plume from source to receptor.

33. A number of investigators [B13, P6, V1] have suggested forms for the vertical dispersion parameter. The following scheme of Smith [S1] and Hosker [H8] is used, since it is able to take account of the surface roughness, z_0(m), of the site:

$$\sigma_z = g(x)\, F(x, z_0) \qquad (10)$$

where $g(x) = ax^b/(1+cx^d)$ and $F(x,z_0) = \ln[px^q[1+(rx^s)^{-1}]]$ when $z_0 > 0.1$ m and $F(x,z_0) = \ln[px^q(1+rx^s)^{-1}]$ when $z_0 \leq 0.1$ m. The parameters a, b, c, and d depend on the atmospheric stability class, and the parameters p, q, r, and s depend on the surface roughness. Representative values are given in Table 3.

34. Equations (7) to (10) provide a relatively simple method for calculating long-term average air concentrations due to a specific source. Wherever possible, site-specific values should be used for the meteorological and release parameters appearing in the equations. In the absence of site-specific data, the representative values listed in Table 4 give reasonable estimates of air concentrations. Values of λ, v_d and Λ should be chosen for the radionuclide of interest.

35. One aim of applying the above method is to derive long-term average dilution factors, C_a/Q, for downwind distances between 1 and 2,000 km from the source. The results of the calculation are given in Table 5. A long-lived radionuclide was assumed so that radiological decay could be neglected. The parameter values in Table 4 were used and the deposition velocity v_d and washout coefficient Λ were set to representative values of 0.002 m s^{-1} and 0.0001 s^{-1}, respectively. Precipitation was assumed to occur 500 hours per year, 80% of the time during class D conditions and 20% during class C, at an average rate of 1.5 mm h^{-1}. The washout time t_s was assumed to be equal to the travel time t_t between source and receptor for $t_t < 4$ hours and equal to $t_t/2$ for $t_t > 24$ hours; in the range $4 < t_t < 24$, t_s was assumed to vary linearly between t_t and $t_t/2$.

36. The variation of air concentration with downwind distance beyond 1 km can be approximated by the following simple function, which was used in previous UNSCEAR assessments:

$$C_a(x) = D_1 Q\, x^{-n} \qquad (11)$$

where D_1 is the dilution factor at 1 km (s m^{-3}) and x is the downwind distance (km). Figure II shows that equation (11) gives a very good representation of the detailed results of Table 5 and can therefore be used to estimate air concentrations in place of equations (7) to (10) if, for example, site-specific data are not available. The best approximation to the calculated results is obtained with values for D_1 and n of 5.3 10^{-7} s m^{-3} and 1.42, respectively. The value for n is similar to the value of 1.5 used in previous UNSCEAR assessments. The value for D_1 is lower by a factor of 6 than the value of 3 10^{-6} s m^{-3} suggested in the UNSCEAR 1982 Report [U6]; this value reflects concentrations at a location toward which the wind blows about 50% of the time, whereas the currently recommended value of 5 10^{-7} s m^{-3} assumes a uniform wind rose at the point of release.

37. The variability in calculated results has been investigated by altering the parameter values used in equations (7) to (10). The meteorological parameters were varied to cover the range of conditions that could occur from time to time. The variability in deposition velocity and washout coefficient reflects the values associated with different radionuclides. Each parameter was varied in turn, holding all other parameters at the values given above. Results are shown in Table 6 in terms of D_1 and n, the parameters required to implement equation (11). D_1 is relatively insensitive to changes in the values of the parameters except for wind speed and release height; n is sensitive to these parameters, as well as to deposition

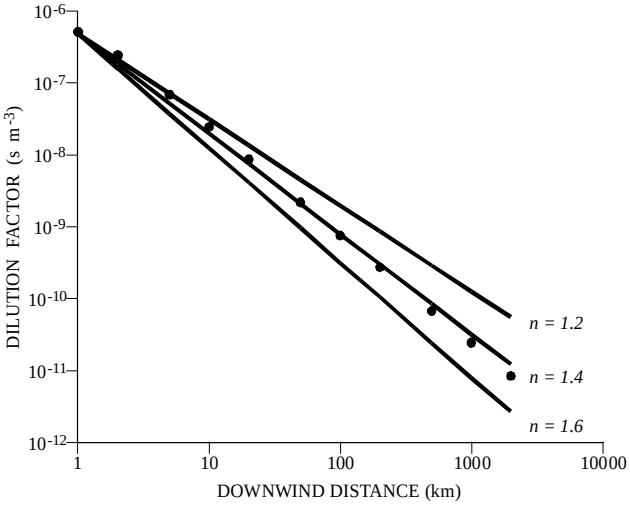

Figure II. Dilution factor for estimation of air concentrations at distances from a surface release determined from Gaussian plume model calculation (points) compared to power-function representations of the form $5\ 10^{-7}\ r^{-n}$.

velocity and inversion height. Release heights can vary from low-level building vents to stacks of 100 m or more. Building entrainment may reduce the effective release height to some extent. The representative height of 30 m has been retained as in earlier UNSCEAR assessments for estimating collective doses following releases from nuclear installations. Individual dose evaluations could depend more critically on the release height assumption. As an example, calculations indicate that for release from a stack of 150 m height, the collective dose in the local and regional area per unit release would be about 25% of that estimated for a 30 m stack. The model is not very sensitive to roughness length, washout coefficient, or the frequency of stability classes. Thus, adequate estimations can be made using the representative values suggested for these parameters without the need for site-specific data. Although wet deposition is very effective at removing material from the plume, precipitation occurs less than 10% of the time and has little effect on long-term average air concentrations. However, reliable values of the washout coefficient are needed to calculate accurately the amount of material deposited on the ground and on vegetation by wet deposition.

38. The results in Table 6 can be used to interpolate the values of D_1 and n that most closely represent meteorological conditions at the site and the radionuclides of interest. Equation (11) can then be used to estimate air concentrations at the downwind distance in question. For noble gases, which do not deposit, a value of n equal to about 1.2 should be used as long as other parameter values remain near the representative values defined here. Tritium should also be assigned a value of 1.2, since most tritium deposited under dry conditions is quickly re-emitted to the atmosphere. Carbon-14 is efficiently deposited and partially returned to the atmosphere through plant and soil respiration. On balance, it is recommended that the index value of 1.4 be used for this radionuclide. For calculation of radionuclide concentrations at a specific site, values of D_1 taken from Table 6 should be modified to reflect the frequency with which the wind blows towards the location of interest. For the purposes of calculating representative population doses using the method presented in this Annex, a uniform wind rose was assumed, with a frequency of 1/12, or 0.083, averaging over 12 sectors.

39. The long-term, sector-averaged Gaussian plume model has been extensively tested at local distances. When used with site-specific meteorological data, the uncertainties in its predictions are less than a factor of 2 within 10 km of the source and less than a factor of 4 between 10 and 100 km of the source [C10, H6, R4]. Use of the model is therefore adequate for local assessments. Validation of the model on regional scales is more difficult. Few point sources are strong enough or emit a unique enough contaminant to be detected unambiguously at downwind distances greater than 100 km. Thus few data from routine releases can be used to test the model. Regional-scale tracer studies have been carried out, but only over short periods of time. These must be considered case studies that provide information only for the meteorological conditions prevailing at the time of the release. They cannot be used to infer long-term average air concentrations.

40. The problem of acid precipitation has driven the development of a number of models that simulate the long-range transport of air pollutants [J3]. These models are much more sophisticated than the Gaussian model described above in their treatment of plume transport and deposition and can track pollutants through space- and time-varying meteorological conditions. They are moderately successful in predicting the broad features of the concentration field on regional scales. However, they require considerable expertise, computer resources, and input data to run and are therefore unsuited to the types of assessments performed by the Committee. Comparisons of their predictions with those of the Gaussian model would help to establish the validity of the latter, but such studies have not yet been done.

41. Although the accuracy of the predictions of the Gaussian model beyond 100 km is difficult to quantify, a number of factors suggest that the model overestimates true concentrations at this range:

(a) The model assumes that the plume travels in a straight line from source to receptor. In reality, variations in wind direction will generally lead to quite complicated trajectories that increase the travel time between source and receptor and provide the opportunity for enhanced mixing.
(b) The model assumes that the stability class in effect at the start of the release remains in effect until the plume reaches the receptor. In reality, a plume travelling over hundreds or thousands of kilometres

will experience several diurnal cycles and a full range of atmospheric stabilities. A plume that has undergone one or more unstable periods will be mixed through a deep vertical layer. It will remain well mixed through subsequent night-time stable periods and not be confined beneath a low capping inversion, as is assumed in the model;

(c) The model assumes that the plume is transported with the wind speed at the effective release height. In reality, as the plume mixes to greater heights, the effective transport velocity must be averaged over deeper layers. Since wind speeds generally increase away from the ground, the result is extra dilution and lower concentrations;

(d) The model assumes that the terrain over which the plume passes is flat, a supposition unlikely to hold over regional distances. Complex topography will tend to increase turbulence levels and deflect the plume trajectory, thereby reducing concentrations.

42. In contrast to the model features mentioned above, the procedure for estimating plume depletion due to dry deposition is not conservative. Material is assumed to be lost uniformly over the entire depth of the plume when in reality it is lost only at the deposition surface. Horst [H7] showed that this approach underestimates airborne concentrations by an amount that increases with increasing atmospheric stability, greater downwind distances, and larger deposition velocities.

43. Thus, the accuracy of the Gaussian model at regional scales is unknown, and uncertainties are large, but probably within a factor of 10 for relatively simple situations. The uncertainties would be somewhat smaller for population doses since the concentration averaged over all distances and directions is probably better known than the concentration at a point.

44. In summary, the value of the dilution factor, D_1, of 5 10^{-7} s m^{-3} is assumed by the Committee to be representative for evaluating collective doses per unit release when site-specific data are not available. The value is not very sensitive to variations in meteorological or deposition parameters. The release height can be of greater influence and, if known to be different from the representative value of 30 m, should be taken into account. The index parameter, n, is more variable than the dilution factor with respect to meteorological and deposition conditions, but a value of 1.2 for noble gases and tritium and 1.4 for other radionuclides should provide reasonable estimates of air concentrations.

II. EXTERNAL IRRADIATION

45. External irradiation from radionuclides naturally present in the environment or released from man-made practices or events is usually an important component of the exposure of human populations. These exposures derive primarily from gamma radiation arising from the decay of these radionuclides at locations outside the human body. Secondarily, exposures to the skin from beta radiation may be considered. The methods used by the Committee to estimate external exposures from the various sources are reviewed in this Chapter.

A. COSMIC RAYS

46. Cosmic rays originate in outer space; they consist primarily of protons and alpha particles. Interactions in the upper layers of the earth's atmosphere create secondary components; the more important secondary particles from a dose-assessment view are muons, neutrons, electrons, positrons, and photons. Exposure to cosmic rays is strongly dependent on altitude and weakly dependent on latitude. Dose assessments are based on both measurements and calculations of the radiation transport to infer the dependence on altitude. At lower levels of the atmosphere and at sea level, the dependence on the 11−year solar cycle is small compared to the uncertainty in the estimates and is currently ignored.

47. The method used by the Committee to assess doses from the photon and directly ionizing component of cosmic radiation at sea level has not changed substantially in many years. In the UNSCEAR 1977 Report [U7] the basic value was considered to be the ion-pair production rate, for which a value of 2.1 cm^{-3} s^{-1} was adopted. This value was converted to a dose rate of 32 nGy h^{-1} and has been assumed to be numerically equal to the effective dose rate [U3, U4]. A mean shielding factor of 0.8 has been applied to derive an indoor effective dose rate of 26 nSv h^{-1}. With the further assumption that the average fraction of time spent indoors is 0.8 [U3, U4], the annual effective dose from the ionizing component of cosmic rays at sea level is judged to be 240 μSv. Estimates of cosmic ray dose rates at elevations above sea level are obtained using a procedure published by Bouville and Lowder [B12]:

$$\dot{E}_I(z) = \dot{E}_I(0)\,[0.21\, e^{-1.649z} + 0.79\, e^{0.4528z}] \qquad (12)$$

where $\dot{E}_I(0)$ is the dose rate at sea level, 240 μSv a^{-1}, and z is the altitude in km. The dose rate from the photon and ionizing component is known to vary with latitude, but the variation is small. The dose rate is about 10% lower at the geomagnetic equator than at high latitudes.

48. For the neutron component of the cosmic radiation exposure, the radiation field and the estimates of effective dose have been more uncertain owing to a lack of measurements. Recent measurements and calculations are beginning to provide clarification. Because earlier instrumentation had a low response to high-energy neutrons, which are an important component of the spectrum, some increases in the fluence rate and effective dose are being suggested. Measurements made using a Bonner sphere spectrometer [R3, S8] at the top of the Zugspitze mountain in Germany (altitude 2,963 m, atmospheric depth 718 g cm^{-2}) and associated calculations give a fluence rate of 0.126 ± 0.01 cm^{-2} s^{-1} [S9]. Attenuation with altitude was described using the function $e^{-0.00721p}$, where p (g cm^{-2}) is the atmospheric depth. From this, a fluence rate at sea level (p = 1,033 g cm^{-2}) of 0.013 ± 0.001 cm^{-2} s^{-1} can be derived. Measurements also with Bonner sphere spectrometers gave a value of 0.0133 ± 0.001 cm^{-2} s^{-1} at about sea level for a geomagnetic latitude of 53°N near Braunschweig in Germany [A6], and a value of 0.0123 cm^{-2} s^{-1} at sea level for a geomagnetic latitude of 45°N in Hampton, Virginia in the United States [G3]. The effective dose (isotropic) corresponding to a fluence rate of 0.013 cm^{-2} s^{-1} obtained by applying a neutron fluence energy distribution weighting factor of 200 pSv cm^2 [S9] (equal to 720 nSv h^{-1} per neutron cm^{-2} s^{-1}) is 9 nSv h^{-1}. Birattari et al. [B14], using an extended range remmeter, reported a value of 9 nSv h^{-1} (±5%) in agreement.

49. The shape of the neutron energy spectrum at habitable altitudes is considered to be relatively invariant, and therefore the fluence to effective dose (isotropic) conversion coefficient is expected to be generally valid. On this basis, the annual effective dose rate from neutrons at sea level would be estimated to be 80 μSv a^{-1}. This is substantially larger than the value of 30 μSv a^{-1} used in the UNSCEAR 1993 Report [U3] and is still subject to great uncertainty; the main factor in the increase in the calculated dose is the inclusion of high-energy neutrons. With the application of a shielding factor of 0.8 and an occupancy factor of 0.8, the annual average effective dose at sea level is estimated to be 65 μSv at geographic latitudes between about 40° and 50°.

50. For calculations of outdoor cosmic ray neutron dose rates at other altitudes, the relation between height, h_v, in km, above sea level and atmospheric depth [R3] is, for p > 230 g cm^{-2},

$$h_v = 44.34 - 11.86\, p^{0.19} \qquad (13)$$

Both altitude and latitude variations in the cosmic ray neutron dose rate must be known to determine the population-weighted average exposure of the world population. Calculations of dose from cosmic rays to airline crews and passengers are based on measurements and on detailed calculations using radiation-transport codes tailored to follow the altitude and latitude of a particular flight.

51. The fluence of neutrons, which arise from collisions of high-energy protons within the upper atmosphere, is strongly influenced by geomagnetic latitude. This variation at habitable altitudes has not been satisfactorily quantified, as measurements at different latitudes have not always been comparable. Recent measurements at high altitudes have shown a variation by a factor of about 4 [G3], with the lower values near the equator. These results support the calculations of Florek et al. [F3], who used the Los Alamos Lahet Code System (LCS) to simulate neutron fluence as a function of latitude. Their results are expressed in terms of k_φ, a latitude coefficient, as follows:

$$\dot{E}_N(\text{lat}) = \dot{E}_N(90)\, k_\phi(\text{lat}) \qquad (14)$$

with k_φ ranging from 1.0 at 90° to 0.8 at 47°, 0.6 at 42°, 0.4 at 35° and 0.2 at the equator. The application of this relationship to available measurement results is discussed in Annex B, *"Exposures from natural radiation sources"*.

B. NATURALLY OCCURRING RADIONUCLIDES

1. Exposure processes

52. Many radionuclides occur naturally in terrestrial soils and rocks and in building materials derived from them. Upon decay, these radionuclides produce an external radiation field to which all human beings are exposed. In terms of dose, the principal primordial (half-lives comparable to the age of the earth) radionuclides are ^{40}K, ^{232}Th, and ^{238}U. Both ^{232}Th and ^{238}U head series of radionuclides that produce significant human exposures. The two series are listed and discussed fully in Annex B, *"Exposures from natural radiation sources"*.

53. The decay of naturally occurring radionuclides in soil produces a gamma-beta radiation field in soil that also crosses the soil–air interface to produce exposures to humans. The main factors that determine the exposure rate to a particular individual are the concentrations of radionuclides in the soil, the time spent outdoors, and the shielding by buildings. However, as the materials of which most buildings are built also contain radionuclides, the shielding by buildings of the outdoor radiation field is often more than offset by the presence of additional radionuclides in the building materials.

2. Methods for estimating exposures

54. Two methods of evaluating external exposures from naturally occurring radionuclides have been used by the Committee. The first is simply to summarize directly measured external gamma dose rates in air outdoors and indoors, subtracting the dose rate due to cosmic rays. The second is to calculate the external gamma dose rates in air from measurements of the concentrations of the relevant radionuclides in soil. The two methods have provided generally consistent estimates of exposure.

55. Surveys with direct measurements of dose rate in air from naturally occurring terrestrial radionuclides have been made in most inhabited regions of the world. In the UNSCEAR 1993 Report [U3], data were included for countries or regions in which three fifths of the world population resides. Country average dose rates ranged from 24 to 160 nGy h^{-1}, with a population-weighted average of 57 nGy h^{-1}. The population-weighted average derived from this large sample was assumed to provide a representative global value of outdoor external exposure.

56. Surveys to determine the concentrations of radionuclides in soil have also been made. These results can be related to exposures by using estimates of the dose rates in air per unit concentration of radionuclide in soil. The Committee has relied on the calculations of Beck [B8] for many years. Extensive Monte Carlo calculations of kerma in air and of organ dose for terrestrial gamma rays have been reported by Petoussi et al. [P4], Saito et al. [S5], and Eckerman and Ryman [E7]. Results from three separate calculations are included in Table 7; the values are quite similar and can be considered equal. Uncertainty in the assumed average composition of soil could lead to differences of greater magnitude [E7].

57. Absorbed dose rates in air indoors have also been extensively measured. The values reported in the UNSCEAR 1993 Report [U3] covered areas in which over a third of the world population lives. Country averages ranged from 20 to 190 nGy h^{-1}, with a population-weighted average of about 80 nGy h^{-1}. The population-weighted average of the ratio of indoor to outdoor dose was 1.4. Some of the outdoor measurements may have been influenced by the presence of buildings nearby. The value of the indoor–to–outdoor ratio is very sensitive to the structural properties of buildings (materials and thickness).The building materials act as sources of radiation and also as shields against outdoor radiation. In wooden and lightweight houses, the source effect is negligible, and the walls are an inefficient shield against the outdoor sources of radiation, so that the absorbed dose rate in air could be expected to be somewhat lower indoors than outdoors. In contrast, in massive houses made of brick, concrete or stone, the gamma rays emitted outdoors are efficiently absorbed by the walls, and the indoor absorbed dose rate depends mainly on the activity concentrations of natural radionuclides in the building materials. Under these circumstances, the indoor absorbed dose rate is generally higher as a result of the change in source geometry, with the indoor–outdoor ratio of absorbed dose rates in air between 1 and 2.

58. The Committee has used a coefficient of 0.7 Sv Gy^{-1} to convert absorbed dose in air to effective dose equivalent and effective dose. This result was based on an analysis in the UNSCEAR 1982 Report [U6], and more recent calculations have confirmed the validity of this value for adults. However, newer calculations [P5, S11] using Monte Carlo radiation-transport codes indicate that higher values should be used for infants and children. These values, given in Table 8 for average energies of gamma rays, are 0.9 Sv Gy^{-1} for infants and 0.8 Sv Gy^{-1} for children.

59. In order to combine indoor and outdoor dose rates to compute total doses, the Committee continues to use an indoor occupancy factor of 0.8, which implies that people spend 20% of the time outdoors, on average, around the world. The estimated 80% of time spent indoors is considered likely to be low for industrialized countries in temperate climates and high for agricultural countries in warm climates.

C. RADIONUCLIDES IN AIR: CLOUD SHINE AND IMMERSION EXPOSURE

1. Exposure processes

60. Following the release of radionuclides to the atmosphere and before their deposition onto the ground, human beings may receive external exposure. Two situations are usually distinguished: external exposure from the cloud passing overhead (referred to as “cloud shine”) and external exposure from radionuclides in air surrounding the human body (referred to as “immersion”). The radiation dose from immersion is nearly always much larger than that from cloud shine. The dose from immersion can be readily calculated from the measured, integrated concentrations of radionuclides in air. The dose from cloud shine is rarely calculated; its importance would be significant only if other exposure pathways were absent. One such example would be for persons underneath an elevated, passing plume.

61. Effective doses from immersion are typically calculated for gamma-emitting radionuclides, but beta and even alpha particles can also produce external doses to the skin. Some radionuclides, notably ^{85}Kr, which emits a weak beta particle, produce nearly all of their dose via the pathway of immersion.

2. Methods for estimating exposures

62. Because of their relative insignificance, the Committee has seldom considered external exposures from cloud shine or immersion. Exceptions were made for the Chernobyl accident and for the release of noble gases from reactor operations. Since initial estimates of such exposures were made, tissue-weighting factors and terminology to describe equivalent and effective doses have changed [I1], and newer calculations of dose rates from immersion have been published [E7]. The net changes in the calculated numbers appear to be small.

(a) Atmospheric nuclear testing

63. Although the potential pathways of cloud shine and immersion were considered in the first report of the

Committee, the UNSCEAR 1958 Report [U13], the doses from these pathways for radionuclides released from explosions of nuclear weapons have not been evaluated. The conclusion was reached that, except at the immediate site of the explosion, external irradiation from airborne material is negligible in comparison with external irradiation from fission products deposited on the ground. As much of the material from nuclear explosions was injected into the stratosphere or high troposphere, most of the short-lived radionuclides potentially responsible for the majority of dose from cloud shine or immersion would have decayed before reaching the earth's surface.

(b) The Chernobyl accident

64. Doses from "external irradiation during cloud passage" were calculated for the releases of radionuclides from the Chernobyl accident [U4]. Although exposure rates could in theory be measured directly, in practice it is generally impossible to distinguish this smaller component from radiation arising from material deposited on the ground. Doses can, however, easily be calculated from measured air concentrations or inferred from measured deposition densities.

65. The cloud-gamma dose for radionuclide i is evaluated from the formula

$$E_i = C^*_{a,i}\, d_{c,i}(1-F_0) + C^*_{a,i}\, d_{c,i}\, F_0\, F_s \qquad (15)$$

where E is the effective dose (Sv) from external radiation during cloud passage; C_a^* is the integrated concentration in outdoor air (Bq d m^{-3}); d_c is the effective dose coefficient per unit integrated air concentration (Sv per Bq d m^{-3}); F_0 is the indoor occupancy factor (the fractional time spent indoors); and F_s is the building shielding factor (the ratio of indoor to outdoor dose rate).

66. The first term in equation (15) is the component received while the individual is outdoors, and the second term is the component received indoors. At the time of the Chernobyl assessment, values from Kocher [K7] were used; these values were for $H_E + 0.01H_{skin}$ rather than E. The values used then and the newer recommended values of $H_E + 0.01H_{skin}$ from Eckerman and Ryman [E7] are listed in Table 9.

67. For the Chernobyl assessment, an indoor occupancy factor of 0.8 and a building shielding factor of 0.2 were used for all countries. The values of these factors had been used previously by the Committee [U6, U7]. It was noted, however, that measurements as well as calculations of the shielding factor afforded by buildings showed a large variation, depending on the type of building [C8, M6, S6, U4].

68. To make the above calculation, it is necessary to know the integrated concentration in air of the many short-lived radionuclides. In some countries, complete data were available. In others, data for only one or a few radionuclides were available. In the latter case concentrations of other radionuclides were inferred from ratios measured in nearby countries. In some cases, no measured air concentrations were available, so the integrated air concentration of ^{137}Cs was inferred from its ground-deposition density and a nominal quotient of ground deposition to integrated air concentration of 1,000 m d^{-1} [U4]; the integrated air concentrations of other radionuclides were then inferred from the ratios to ^{137}Cs measured at other locations.

(c) Nuclear installations

69. During the operation of nuclear reactors, several fission noble gases are released, as is the activation radionuclide ^{41}Ar. Among the more prominent fission noble gases are ^{133}Xe from pressurized water reactors and ^{85}Kr, ^{87}Kr, ^{88}Kr, ^{133}Xe, ^{135m}Xe, ^{135}Xe and ^{138}Xe from boiling water reactors [U6]. Much of the dose from these (and other) radionuclides is delivered by the pathway of cloud shine and immersion. Later reports [U3, U4] of the Committee refer to the models developed in the UNSCEAR 1982 Report [U6]. Thus, while the absolute amounts and the relative mixture of radionuclides have changed, the dose-assessment methods have not. As most of the fission-product noble gases and the activation gas are short-lived, attention has been focused on exposures to nearby residents.

70. When the radionuclide is uniformly distributed in the atmosphere or the photon energy is sufficiently low that this is a reasonable approximation over the volume of a plume, then the simplest calculational method is the semi-infinite cloud model. This method assumes that the radiation from the cloud is in electronic equilibrium, so that the energy absorbed by a given volume element equals that emitted by the same element. For a point at ground level, only half the space contributes to the dose, so that the energy absorbed is divided by two. The absorbed dose rate in air is then given by

$$\dot{D}_a = 0.5\frac{k}{\rho_a}\, C_a \sum_{i=1}^{n} F_i E_i \qquad (16)$$

where $\dot{D}_a$ is the absorbed dose rate (Gy h^{-1}); C_a is the average activity concentration of the radionuclide in the cloud (Bq m^{-3}); ρ_a is the mass density of air (kg m^{-3}); F_i is the fraction of photons of initial energy E_i (MeV) emitted per disintegration; and k is a conversion coefficient from energy deposition per unit mass and unit time to absorbed dose rate equal to 5.76 10^{-10} Gy h^{-1} (MeV $kg^{-1})^{-1}$. A modified version of this model, where F_i and E_i pertain to beta emissions, is used for beta irradiation of the skin.

71. If the distribution of the activity concentration in the plume is sufficiently non-uniform to invalidate the above approach, then a finite cloud model must be used. Such a condition arises near the source, when persons are not in

the cloud but receive dose from an overhead plume. In this model, the cloud is simulated by a number of small-volume sources, and integration is performed over these sources. The calculation proceeds by finding the photon flux density, summing over all the decay energies for the radionuclide of interest and then converting to absorbed dose. The basic expression for the photon fluence due to the fraction F_i of photons of energy E_i emitted per disintegration is [N2]

$$\phi_i = \int_V \frac{X_V F_i B_{en}(E_i, \mu_i x) e^{-\mu_i x}}{4 \pi x^2} dV \qquad (17)$$

where φ_i is the photon fluence; X_V is the concentration of the atoms of each radionuclide in volume element dV; μ_i is the linear attenuation coefficient, x is the distance from the volume element dV; and $B_{en}(E_i, \mu_i x)$ is the energy absorption build-up factor at a distance x for a radiation of initial energy E_i, having an attenuation coefficient μ_i. This integral is evaluated numerically.

72. In general terms, the Committee has considered 0.7 Sv Gy^{-1} to be the most appropriate average value of the quotient of effective dose rate to absorbed dose rate in air for males and females for environmental exposures to gamma rays. However, when the absorbed dose in air is the result of a calculation such as is described in this Section, then there are sufficient data on the photon energy spectrum to use more precise conversions. These conversion coefficients have been derived for infants, children, and adults by Saito et al. [S5, S11], based on a semi-infinite cloud model. These age-dependent results have not been used by the Committee, but the energy-dependent variations for the adult have been incorporated into the radionuclide-specific results [E7].

73. Based on the types of calculations indicated above, the Committee has estimated values of the collective effective doses from immersion exposure per unit release of fission noble gases and the activation gas ^{41}Ar [U6]. These calculations are updated in Table 10. On the assumption of a semi-infinite cloud and uniform concentrations over the mean paths of gamma rays in air, the effective dose rates to the adult per unit concentration of the radionuclide in air, d_i, have been calculated [E7]. The collective dose over the local and regional areas is evaluated as follows:

$$S_i = \int C_{a,i}(x)\, d_i\, N\, 2\pi x\, dx \qquad (18)$$

where d_i is the dose factor for radionuclide i, N is the number of inhabitants per unit area, and x is the downwind distance. The concentration of radionuclide i at distance x, $C_{a,i}(x)$, can be determined from equations (7–10). For short-lived radionuclides, radioactive decay during the dispersal time must be taken into account. In this case the concentration is

$$C_{a,i}(x) = C_{a,j}\, e^{-\lambda x/u} \qquad (19)$$

where $C_{a,j}$ was defined in equation (7), λ is the radioactive decay constant (s^{-1}), and u is the wind speed (m s^{-1}) for a given stability class. Since noble gases do not deposit, the wet and dry depletion factors D_w and D_d in equation (7) are set equal to 1 in these calculations.

74. Analytical evaluation of the integral, equation (18), with the expression of equations (7–10) is not possible, so a numerical integration is required. The results are given in Table 10. The radionuclide releases apply to the model site with the meteorological conditions given in Table 4. The release height was 30 m and the population densities were taken to be 400 inhabitants km^{-2} in the local area (1–50 km) and 20 inhabitants km^{-2} in the regional area (50–2,000 km). A similar method could be used to obtain the immersion dose from radon released from mill tailings, but the result is of much less significance than that due to inhalation.

75. The composition of noble gas releases from reactors is variable, depending on the reactor type and discharge delay features. If the composition is not known specifically, representative compositions may be assumed, such as used previously by the Committee and as listed in Table 11. For PWRs, the long-lived noble gas ^{133}Xe predominates with secondary release of ^{135}Xe. For BWRs, the composition includes several short-lived components. For GCRs, the noble gas release is assumed to comprise wholly ^{41}Ar. The dose factors derived in Table 11 to be applied in the general case to noble gas releases are 0.11 man Sv PBq^{-1} for PWRs, 0.43 man Sv PBq^{-1} for BWRs, and from Table 10 (^{41}Ar) 0.90 man Sv PBq^{-1} for GCRs. Because of changes in the parameters and calculational procedure, these values are slightly different from those previously derived [J1, U6].

76. For discharges from fuel reprocessing plants, the only radionuclide of interest in terms of cloud dose is ^{85}Kr [U6]. The Committee assessed the dose resulting from discharges of ^{85}Kr from the Windscale plant (Sellafield) between 1975 and 1979 using the methodology provided for the European Community [N2]. The average annual release of ^{85}Kr was 35 PBq and the resulting local and regional collective absorbed dose commitments were as follows: gonads, 0.058; breast, 0.078; red bone marrow, 0.095; lungs, 0.074; thyroid, 0.065; bone lining cells, 0.095; liver, 0.074; skin, 19; and remainder tissues, 0.078 man Gy. The collective effective dose equivalent commitment was estimated to be 0.074 man Sv from the cloud gamma irradiation using the conversion coefficients of Poston and Snyder [P3]. A further contribution from the beta irradiation to the skin is 0.19 man Sv, for which a skin-weighting factor of 0.01 is applied. Thus, the normalized collective effective dose commitment, $H_E + 0.01\, H_{skin}$, for this site is 0.0075 man Sv PBq^{-1}.

(d) Globally dispersed ^{85}Kr

77. The model used to calculate the global collective dose commitment from ^{85}Kr released at fuel reprocessing plants is given in the UNSCEAR 1982 Report [U6]. A two-compartment model similar to that proposed by Kelly et al. [K3] is used in which the released krypton is assumed to be instantaneously dispersed throughout the troposphere of the northern hemisphere, which is assumed to have a height of 10 km and a mass of $1.9\ 10^{18}$ kg (1 m^3 of air corresponds to 1.2 kg). Exchanges take place between the troposphere of the two hemispheres with a half-time of about two years. Within a few years the ^{85}Kr becomes uniformly dispersed, and the sole removal mechanism is radioactive decay.

78. The whole-body absorbed dose commitment per unit time integral of air concentration of ^{85}Kr was estimated to be $4.3\ 10^{-9}$ Gy (Bq a $kg^{-1})^{-1}$ [N2], and the dose commitment to the skin from the beta irradiation was $5.4\ 10^{-7}$ Gy (Bq a $kg^{-1})^{-1}$. These values were restated in the UNSCEAR 1988 Report [U4] to correspond to a collective effective dose equivalent commitment from ^{85}Kr of 0.17 man Sv PBq^{-1}, assuming a world population of $4\ 10^9$. This value was then scaled to a value of 0.2 man Sv PBq^{-1} for the world population of $4.6\ 10^9$ during the 1985–1989 period. Newer calculations [E7] indicate a value for effective dose equivalent, H_E, of $4.51\ 10^{-9}$ Sv (Bq a $kg^{-1})^{-1}$ and for skin, H_{skin}, of $5.00\ 10^{-7}$ Sv (Bq a $kg^{-1})^{-1}$, or 7.92 nSv (Bq a $m^{-3})^{-1}$ ($H_E + 0.01\ H_{skin}$). With this slight change and for a world population of $6\ 10^9$, the normalized effective dose commitment becomes 0.22 man Sv PBq^{-1}.

D. RADIONUCLIDES DEPOSITED ON SOIL

1. Exposure processes

79. Radionuclides released to the atmosphere undergo decay in transit or are deposited on the earth's surface by wet or dry deposition within relatively short periods. There follows a generally longer period in which the radionuclides on the terrestrial surface will eventually decay and produce external radiation exposure and dose to the population living in the areas. Radionuclides are initially deposited on the upper surface of the soil, but they quickly weather into the first centimetre of soil, especially if they are deposited via rainfall. This weathering effect and also the fact that the soil surface is not a smooth plane (soil roughness) reduce the radiation field at the generally used reference height of 1 m above the soil surface. Other mechanisms, such as plowing and countermeasures, can reduce the exposure rate, but such processes have not been considered in assessments of the Committee.

80. Following the deposition of radioactive material from the Chernobyl accident, several groups observed that the measured external gamma exposure rate decreased more rapidly over urban surfaces than over grass surfaces [J2, K6, S7]. Although varied, these results were consistent with the loss of half of the material with a half-time of seven days and the other half being firmly fixed on urban surfaces. This urban runoff effect was reflected in the Chernobyl assessment in the UNSCEAR 1988 Report [U4] by applying these coefficients to that portion of a country's population considered to be urban. Such an effect was not considered in the Committee's assessment of dose from nuclear weapons fallout.

2. Methods for estimating exposures

81. The Committee has traditionally used two approaches to estimate the external doses that result from the deposition of radionuclides on soil surfaces: direct measurements and calculations based on radionuclide deposition densities, which are the same procedures as used to evaluate exposures from naturally occurring radionuclides. As the calculational approach is more easily applied and as it is not always possible to measure very low dose rates, it is results of this approach that are more generally available.

(a) Atmospheric nuclear testing

82. The evaluation of radiation doses from fallout of radionuclides onto the earth's surface following the testing of nuclear weapons in the atmosphere was one of the earliest problems to be addressed by the Committee and one that has been regularly considered. The general method of assessing radiation doses from fallout from nuclear tests is indicated in Figure I. Within this model the external effective dose commitment, E_c, for a specific radionuclide released in an atmospheric test is

$$E_c = P_{01} P_{12} P_{25} A_0 = P_{25} F \qquad (20)$$

where A_0 is the amount released, P_{01} is the integrated concentration of a radionuclide in air at a specified location divided by the amount released, P_{12} is the quotient of the deposition density and the integrated air concentration, and P_{25} is the quotient of the effective dose commitment and the deposition density. The second part of the equation represents a more direct method of evaluation, namely beginning with the measured deposition density F (also equal to $P_{01}P_{12}A_0$) and multiplying this by the transfer coefficient P_{25}.

83. The P_{25} transfer coefficients for external irradiation have been calculated by multiplying the dose-rate conversion coefficients for radionuclides deposited on the ground, derived from Beck [B9], by the mean lifetime of the radionuclide and by an average factor accounting for air–to–tissue dose conversion, indoor occupancy in buildings (80% assumed) with a shielding factor of 0.2. The latter factor is 0.7 Sv Gy^{-1} (effective dose rate in the body per unit absorbed dose rate in air) times 0.36 (0.2 outdoor occupancy plus 0.8 indoor occupancy times 0.2

building shielding). For short-lived radionuclides (all except ^{137}Cs for fallout from nuclear testing) the dose-rate conversion coefficient applying to a plane source has been used. For ^{137}Cs, the dose-rate conversion coefficient applying to an exponential concentration profile in the ground of mean depth 3 cm is used. The indoor occupancy, as well as the shielding factor, can vary a great deal among different populations and is a source of uncertainty in the calculations of external dose. Also, the different behaviour of radionuclides deposited in urban and rural environments has not been taken into account for estimates of dose from nuclear weapons fallout. This difference was, however, considered for the assessment of doses from the Chernobyl accident (see below).

84. The P_{25} transfer coefficients that are used to estimate external doses from deposited radionuclides from fallout from nuclear testing are presented in Table 12. Transfer coefficients for many other radionuclides can be derived from the basic data of Beck [B9]. In earlier assessments the Committee assumed a plane source to be appropriate for short-lived radionuclides, however, to account for ground roughness, it is more realistic to assume an exponentially distributed source with a relaxation depth of 0.1, 1, and 3 cm for radionuclides of half-lives <30 days, 30–100 days, and >100 days, respectively. This change reduces the doses by about 15%–50%, but it does not have a significant impact on the calculated total dose from nuclear weapons fallout, which is dominated by the dose from ^{137}Cs.

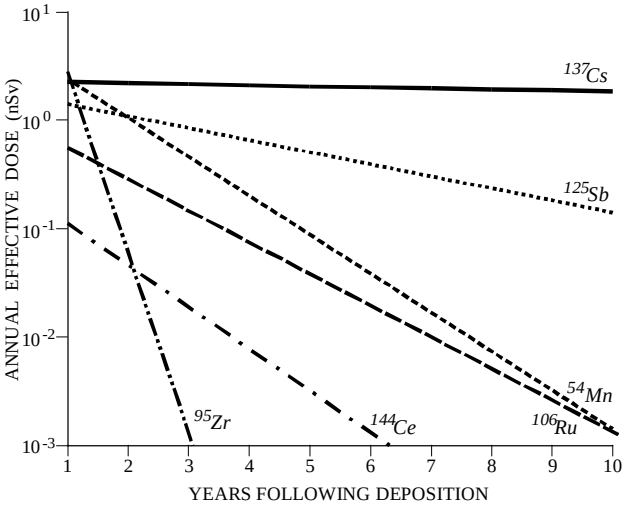

Figure III. External exposure following unit deposition (1 Bq m^{-2}) of radionuclides.

85. An indication of annual contributions to doses from external exposure following a single deposition event may be of interest, although the analysis is simple, as it depends only on the radioactive decay of the radionuclides. The time course of contributions to dose from unit deposition density of the radionuclides is illustrated in Figure III, and the annual average doses are listed in Table 13. Several short-lived radionuclides (^{131}I, ^{140}Ba, ^{141}Ce and ^{103}Ru) make no contributions to external exposure beyond the first year following deposition. The values in Table 13 have been calculated from decayed monthly deposition density, averaged over the year and multiplied by the absorbed dose rate in air per unit deposition density (Table 12, column 3) and by the shielding/occupancy factor of 0.36 and the conversion factor 0.7 Sv Gy^{-1}. The sum of the annual contributions to dose is equal to the dose commitment.

(b) The Chernobyl accident

86. The methods used to calculate external doses caused by the Chernobyl accident were basically those applied to estimate the external doses from radionuclides produced in atmospheric nuclear testing, although several modifications were introduced to account for the shorter term of the release, urban-rural differences, and an improved assessment of the movement of radionuclides into soil. The results of calculations of doses from the Chernobyl accident were presented in the UNSCEAR 1988 Report [U4]. During the first month after deposition, a number of short-lived emitters, including ^{132}Te, ^{132}I, ^{131}I, ^{140}Ba, ^{140}La, and ^{136}Cs, were important components of the total external gamma exposure rate (or dose rate in air). For several months, ^{103}Ru and ^{106}Ru made contributions, but since then only ^{134}Cs and ^{137}Cs have been of significance. Exposure from ^{137}Cs remains significant for several years and must be projected into the future.

(i) First month

87. The outdoor exposure X_1 (C kg^{-1}) during the first month was assessed by four different methods, with the choice dependent on the data available. If continuous or daily data were provided, the exposure rates were integrated. If incomplete data were provided, an attempt was made to fit a power function of the form at^b to the data, where t is time (days) and a and b are constants to be determined. X_1 is then the integral of this function from arrival day 1 to day 30.

88. If measurements of external gamma exposure rate were not available, two approaches were used. If data on the ground deposition of the radionuclides were provided, the exposure rate from each radionuclide was computed using the coefficients published by Beck [B9] for a relaxation depth of 1 mm to account for surface roughness. In several cases only data on the deposition of ^{137}Cs were available, and X_1 was evaluated on the basis of the relationship of the exposure to ^{137}Cs deposition density as measured at a specific location, e.g. Neuherberg, Germany [G2].

89. The effective dose during the first month, E_{e1}, (Sv) was calculated from X_1 by:

$$E_{e1} = AX_1(1 - F_0) + AX_1F_0F_s \qquad (21)$$

where A is the conversion coefficient (23.6 Sv per C kg^{-1}, i.e. 33.7 Gy per C kg^{-1} × 0.7 Sv Gy^{-1}), F_0 is the indoor occupancy factor, and F_s is the building shielding factor. The last two values were taken as 0.8 and 0.2, respectively.

(ii) One month to one year

90. The calculation of external gamma dose beyond one month was based on the measured total deposition of ^{134}Cs and ^{137}Cs and, although less important, ^{103}Ru, ^{106}Ru, and ^{131}I. The conversion coefficients for long-term deposition to dose rate depend on the penetration of these radionuclides into soil. Change with time is accounted for by using coefficients appropriate for a relaxation depth of 1 cm during the first year and 3 cm thereafter. Also, the effect of more rapid removal of radionuclides from urban surfaces was considered.

91. The equation for the calculation of external gamma effective dose, E_{e2}, (Sv) for the time period between one month and one year for radionuclide i is as follows:

$$E_{e2,i} = \left[\frac{F_i}{\lambda_i}\right]\left[d_{e2,i}(e^{-\lambda_i m/12} - e^{-\lambda_i m})\right] \left[1 - F_0(1 - F_s)\right]\left[1 - F_p(1 - F_u)\right] \quad (22)$$

where F_i is the deposition density (Bq m^{-2}); $d_{e2,i}$ is the deposition density to effective dose conversion coefficient during the period between one month and one year (relaxation depth of 1 cm) (Sv per Bq m^{-2}); λ_i is the radioactivity decay constant (a^{-1}); m is a constant equal to one year; F_p is the urban fraction of a country's population; F_u is the fraction of the deposition that remains fixed on urban surfaces (assumed to be equal to 0.5); and F_0 and F_s are as defined previously. Effective dose equivalent conversion coefficients are listed in Table 14.

(iii) Periods beyond one year

92. External effective dose, $E_{e3,i}$, (Sv) for periods beyond one year were evaluated according to the equation

$$E_{e3,i} = \left[\frac{F_i}{\lambda_i}\right]\left[d_{e3,i}\, e^{-\lambda_i m}\right] \left[1 - F_0(1 - F_s)\right]\left[1 - F_p(1 - F_u)\right] \quad (23)$$

where $d_{e3,i}$ is the deposition density to effective conversion coefficient for periods greater than one year. This coefficient is based on a relaxation depth of 3 cm. Values of this coefficient are also listed in Table 14.

(c) Nuclear installations

93. Releases from nuclear installations of radionuclides that contribute to external exposures are, in general, too low to be measured in air or deposition at distances beyond the installation site and point of release. As was discussed in Section I.B.3, long-term average dispersion of radionuclides in air may be estimated using a formulation that combines a dilution factor at 1 km and a power function of distance from the release point. With use of an effective deposition velocity that accounts for both wet and dry deposition, the deposition densities of radionuclides may be estimated. This method is appropriate for routine continuous and near-surface releases from sources such as nuclear installations. The local area of exposure is taken to be 1–50 km surrounding the point of release, and the regional area extends to 2,000 km.

94. In the dispersion estimation method, equation (11), an average dilution factor is assigned at 1 km, namely $5\ 10^{-7}$ Bq m^{-3} per Bq s^{-1} released, and further dispersion reduces the radionuclide concentration in air in inverse proportionality to the 1.4 power of the distance. The air concentration may be related to the deposition density by multiplying by the effective deposition velocity. The general formula for application of the transfer factor method is

$$S_i = 5\ 10^{-7}\, v_g\, P_{25} \left[N_1 \int_1^{50} x^{-1.4}\, 2\pi x\, dx + N_2 \int_{50}^{2000} x^{-1.4}\, 2\pi x\, dx\right] \quad (24)$$

where S_i is the collective effective dose per unit release of radionuclide i (man Sv Bq^{-1}); v_g is the effective deposition velocity (m s^{-1}); P_{25} is the transfer factor from deposition density to dose (Sv per Bq m^{-2}); N_1 is the population density in the local area (inhabitants km^{-2}); N_2 is the population density in the regional area (inhabitants km^{-2}); and x is the distance from the point of release (km). The parameter $x^{-1.4}$ should actually be expressed as $(x/1\ km)^{-1.4}$ to rectify the units. The quantity in brackets has the unit number of persons. The population densities applied are those assumed for model reactor site: $N_1 = 400$ inhabitants km^{-2} and $N_2 = 20$ inhabitants km^{-2}. The value of the effective deposition velocity is taken to be 0.002 m s^{-1} for annual average deposition, which is the value for dry deposition alone. In reality, more material is deposited under wet conditions than under dry, and an effective deposition velocity for point sources that includes both wet and dry contributions would range from 0.005 to 0.013 m s^{-1}, depending on downwind distance. However, use of a larger value in conjunction with the power law expression for the air concentration (equation 11) results in a greater estimated activity amount deposited in the local and regional areas than was released to the atmosphere. The most probable explanation for this is that equation 11 overestimates air concentrations, for the reason given in paragraph 41. Although larger (more negative) values of the exponent in the power function could be selected to offset a higher effective deposition velocity, the values of 1.4 and 0.002 m s^{-1} preserve the mass balance to distances of 2,000 km and ensure that doses from airborne and deposited activity are not underestimated. Therefore, these values are used on local and regional scales for purposes of estimating average deposition.

95. Estimates of normalized collective effective doses from external exposure from radionuclides released as particles in airborne effluents from reactors are listed in Table 15. The transfer coefficients P_{25} from deposition density to effective dose were derived from the basic data of Beck [B9]. The collective effective doses per unit release were then estimated using equation (24). Other fission and activation products could be added to Table 15 by applying this method.

96. A representative composition of radionuclides in particulates released in airborne effluents is not easily established because of the large number and varying amounts of radionuclides that may be involved. An earlier approach of the Committee [U6] was to assume equal activity distribution across 18 radionuclides that were commonly reported to be present. A slight variation would be to recognize two groups of radionuclides, one of more dominant contributors to the total activity release and a secondary group. Consistent with reported data [U5, U6] is to assume 90% of the activity of release present as ^{54}Mn, ^{58}Co, ^{60}Co, ^{89}Sr , ^{134}Cs, ^{137}Cs, and ^{140}Ba (including ^{140}La). The radionuclides of the second group, contributing 10% of the activity total, are ^{51}Cr, ^{59}Fe, ^{65}Zn, ^{90}Sr, ^{90}Y, ^{95}Zr (including ^{95}Nb), ^{124}Sb, ^{136}Cs, ^{141}Ce, and ^{144}Ce. Assuming equal contributions to the activity release within each group, weighted average values of the local and regional collective effective doses per unit total (representative) release of particulates are obtained. These results are included in Table 15. Adjusted weightings could be made in specific circumstances, if the exact composition of the release is known.

III. INHALATION EXPOSURE

97. There are two main processes that contribute to internal exposure, the general term used to describe exposures that involve the intake of radionuclides into the body as opposed to external exposure, which is considered in Chapter II above. The two processes are inhalation of contaminated air and ingestion of contaminated foodstuffs. For inhalation, if the time dependent concentration of a radionuclide in air is known, it is a straightforward matter to calculate committed dose by multiplying by a breathing rate and by a dose-conversion coefficient. The ingestion pathway involves additional steps of transfer to plants and animals, from which are derived the foods consumed by humans. For convenience, inhalation exposures are considered in this Chapter and ingestion exposure in the following Chapter.

98. Many of the Committee's past calculations of inhalation doses were performed using a nominal breathing rate of 20 $m^3\ d^{-1}$, or 7,300 $m^3\ a^{-1}$. This generally reflects the concern of the Committee with the collective dose, which is substantially determined by the intake of the adults in the population. For calculating inhalation doses from the Chernobyl accident, inhalation rates of 22 $m^3\ d^{-1}$ for adults and 3.8 $m^3\ d^{-1}$ for infants were used [U4]. The latter values are the same as those used for naturally occurring radionuclides and are derived from the same source [I7].

99. The Committee has generally used the dose coefficients published by ICRP for its evaluations. Initially such values were available only for adult workers, but starting in 1989 age-dependent values have been made available for members of the general public. The latest compilation of values for both ingestion and inhalation is provided in [I5]. The breathing rates now used by ICRP [I4] are indicated in Table 16. An indication is also given in Table 16 of the fraction of the population in each of the six age categories and the age-weighted average breathing rate. The age-weighted value corresponds to 19 $m^3\ d^{-1}$. Considering the uncertainty of the age distribution of the population and the differences between countries, a rounded value of the nominal breathing rate of 20 $m^3\ d^{-1}$ would seem to be appropriate for use in most applications. In assessments of the Committee, the population groups specified as infants, children, and adults are assumed to correspond with the ICRP age categories of 1–2 years, 8–12 years, and >17 years, respectively.

A. NATURAL RADIONUCLIDES

100. Naturally occurring radionuclides are present in the atmosphere owing to their production by cosmic ray interactions, the emanation of gases from soil or building materials and the resuspension of soil particles from the ground surface. The main cosmogenic radionuclides, ^{3}H and ^{14}C, are fairly uniformly dispersed in the atmosphere. Inhalation exposures from these radionuclides are, however, almost completely negligible compared with the ingestion exposures.

101. Soil-derived radionuclides are present in air in variable amounts, depending on local soil, wind, and moisture conditions. In earlier assessments by UNSCEAR [U6, U7], a dust loading of 50 μg m^{-3} was assumed and applied to typical concentrations of natural radionuclides in soil. Some portion of the solid matter in air may not come from the soil, however, but from organic matter, building dusts, smoke, and fly ash from coal burning.

102. A very important contribution to inhalation exposure is made by radon and its decay products. The gas emanates from soil and can enter and attain high concentrations in indoor spaces. Because this exposure component dominates that from all other pathways, it is important that the dosimetry for radon be well established.

103. The ICRP has not provided values of the doses per unit intake for ^{222}Rn and ^{220}Rn and their decay products from application of the respiratory tract model [I4, I5], and the dosimetry for these mixtures is very complex. Because lung cancer has been observed and studied extensively in miners exposed to ^{222}Rn, the ICRP [I13] has adopted a conversion convention for radon exposures that is based on equality of detriments from epidemiological determinations. The detriment per unit effective dose for members of the public is $7.3\ 10^{-5}$ per mSv, and the detriment (to miners) per unit exposure to ^{222}Rn progeny is $8.0\ 10^{-5}$ per (mJ h m^{-3}). Thus, an exposure to ^{222}Rn progeny of 1 mJ h m^{-3} is equivalent to an effective dose of 1.10 mSv. As 1 mJ h m^{-3} is equal to $1.80\ 10^{5}$ Bq h m^{-3} of ^{222}Rn in equilibrium with its short-lived progeny, a dose coefficient of 6.1 nSv per (Bq h m^{-3}) can be derived and applied to equivalent equilibrium concentrations (the activity concentration of radon, in equilibrium with its short-lived progeny, which would have the same potential alpha energy concentration as the existing non-equilibrium mixture). The dosimetric evaluations give dose coefficients in the range 6–15 nSv (Bq h m^{-3})$^{-1}$. The value previously used by the Committee in earlier evaluations [U3, U4], 9 nSv (Bq h m^{-3})$^{-1}$, is within this range and would seem to be still appropriate for use in dose evaluations. An epidemiologically based conversion convention is not available for ^{220}Rn. However, by analogy with the risk determined for ^{222}Rn and by comparing the dose coefficients for ^{220}Rn and ^{222}Rn calculated on a dosimetric basis [I18], a dose-conversion convention of 40 nSv per (Bq h m^{-3}) equilibrium equivalent concentration of ^{220}Rn can be derived; this value is intended to include the dose to organs other than lung due to the transfer of ^{212}Pb from the lung. The half-life of ^{212}Pb is sufficiently long (10.64 h) for this effect to be significant, whereas none of the short-lived progeny of ^{222}Rn is sufficiently long-lived to merit similar consideration.

B. RADIONUCLIDES RELEASED TO THE ATMOSPHERE

104. In its various assessments, the Committee has used the best available estimates of dose per unit intake of radionuclides by inhalation; whenever possible, the values provided by ICRP have been used. The ICRP values have been updated [I4, I5] based on a revision to the ICRP model of the respiratory tract [I6], and age-dependent values for the general public are now provided. The values for radionuclides used by the Committee in its assessments are given in Table 17.

1. Exposure processes

105. Inhalation of radionuclides in air can result from a short-term or continuous release processes. Inhalation is rarely the primary pathway of exposure if radionuclides are released to the atmosphere, but there are some notable exceptions. The importance of radon and its decay products was mentioned in the preceding Section. Another exception involves radionuclides of extremely low biological availability. Such radionuclides pass readily through the gut following ingestion intake, but they can be deposited in the lungs following inhalation intake and be retained for long times. The most notable example of such a radionuclide is ^{239,240}Pu.

2. Methods for estimating exposures

(a) Atmospheric nuclear testing

106. According to the general model developed by the Committee to describe environmental transport processes, the equation for committed effective dose, E_c, (Sv) via inhalation is

$$E_c = P_{01} P_{14} P_{45} A_0 = P_{245} F \qquad (25)$$

where $P_{01}A_0$ is the integrated air concentration (Bq a m^{-3}), P_{14} is the breathing rate (m^3 a^{-1}) and P_{45} is the dose-conversion coefficient (Sv Bq^{-1}) for inhalation. To determine the integrated air concentration, measurements must be made for the entire time that radionuclides remain in air. Since this is not always achieved in practice, the second part of the equation is the more common approach, in which the integrated air concentration is estimated from the deposition density, F. In this case, the transfer coefficient for the inhalation pathway is determined as $P_{245} = P_{14}P_{45}/P_{12}$.

107. The average value of P_{12}, which is also the effective deposition velocity, varies with the precipitation rate at different locations and also with the chemical and physical nature of the radionuclide considered. The average value of P_{12} for particulate material deposited following atmospheric nuclear testing has been estimated to be 1.76 cm s^{-1}, or $5.56\ 10^{5}$ m a^{-1} [B2]. Although this value is based on observations in New York City over several years, measurements in the United Kingdom [C7] and Sweden [B10, D5] are in reasonable agreement after normalization to the same annual precipitation. Furthermore, since the annual rainfall in New York City is fairly close to the population-weighted average for the whole world, the New York value is considered adequate for global average calculations.

108. Values of the transfer coefficient, P_{245}, for the inhalation pathway are listed in Table 18. These update the listing in the UNSCEAR 1993 Report (Table 8, page 127 [U3]). The values are for the adult with a breathing rate of

7,300 m^3 a^{-1} and P_{45} values from Table 17. These transfer coefficients are applicable to the release and deposition conditions of radionuclides in fallout from nuclear tests.

(b) The Chernobyl accident

109. For the Chernobyl accident assessment, a somewhat modified approach was used to account for a filtration effect that reduces the concentrations of radionuclides in indoor air [U4]. The calculation of the inhalation committed effective dose, $E_{h,i}$ (Sv) for radionuclide i was as follows:

$$E_{h,i} = C^*_{a,i} \; B \; d_{h,i}(1 - F_0) + C^*_{a,i} \; B \; d_{h,i} \; F_0 \; F_r \qquad (26)$$

where $C^*_{a,i}$ is the integrated activity concentration of radionuclide i in outdoor air, B is the breathing rate, $d_{h,i}$ is the committed dose per unit intake from inhalation, F_0 is the indoor occupancy factor and F_r is the ratio of indoor to outdoor air concentration. The latter parameter was assigned a value of 0.3 for all countries [C9, R2, U4].

110. If the integrated concentration in air is known, then the calculation is very simple as indicated above. Furthermore, if an average concentration over a one-year period is known, then the calculation is also quite straightforward. It is, however, rather rare that measurements of integrated activity in air are available following accidental releases, especially over a short period of time. In that case the integrated concentration in air is usually estimated on the basis of the deposition density for a particular radionuclide and the effective deposition velocity, as mentioned above. The deposition density divided by the deposition velocity gives the integrated concentration in air.

111. If the relative amounts of the radionuclides released at the time are known and if these releases are concurrent, then the measurement of the deposition density for only one radionuclide in the mixture can be considered sufficient to define the deposition densities of all radionuclides at the time of deposition, if the deposition velocities of the radioelements do not differ significantly. In fact, measurements of the deposition density of a long-lived radionuclide can be made many years after the deposition occurred and used to define the original deposition densities of all radionuclides, provided that the soil is undisturbed and the sampling is deep enough to encompass all of the original deposition.

112. Other methods can be used to define the deposition densities and the integrated air concentrations of radionuclides. Although subject to more error and in need of more sophisticated interpretation, measurements of the external gamma-dose rate in air, of concentrations of radionuclides in foodstuffs, and even of radionuclides in people can be used to estimate the original deposition densities and integrated air concentrations.

(c) Nuclear installations

113. Estimates of inhalation exposure from releases of radionuclides from nuclear installations may be made using the dispersion model presented in Section I.B.3 and the transfer coefficients P_{245}. The results of this calculation are listed in Table 19. These estimates apply to longer-term releases, as the meteorological conditions for the representative site have been averaged over an annual period. The deposition velocity appropriate for near-surface releases of 0.002 m s^{-1} has been used. This is determined mainly by dry deposition, since precipitation can be expected to occur only during a small fraction of the time of plume passage.

114. As discussed above with regard to external exposure (paragraph 96), a representative composition of radionuclides in particulates released in airborne effluents from reactors may be assumed. A weighted average of the collective dose from inhalation exposure per unit release of particulates may then be derived for general application. The values pertaining to the local and regional areas are included in Table 19. The transuranium radionuclides are not normally reported in routine releases from reactors, however for reference purposes, the values are included in Table 19.

IV. INGESTION EXPOSURE

115. Ingestion exposure occurs when radionuclides in the environment enter food chains. This component and that of external exposure are usually the significant and continuing sources of exposure following releases of radionuclides to the environment. Radionuclides released to the atmosphere may deposit onto both terrestrial and aquatic surfaces, for which different calculational methods are required. The terrestrial and aquatic food pathways are considered in separate Sections of this Chapter.

116. Ingestion exposures have been evaluated by UNSCEAR for natural radionuclides present in the environment and for several cases of radionuclide release to the environment, including atmospheric testing, releases from nuclear fuel cycle installations and the Chernobyl accident. For the most part, annual average values have been considered with the aim of evaluating committed exposures. This is adequate for longer-term or continuous releases. Short-term releases at particular times, such as

was the case for the Chernobyl accident, require taking into account some seasonal variations.

A. NATURAL RADIONUCLIDES

117. In the general case, doses from the ingestion of natural radionuclides in foods and drinking water have been estimated from measured concentrations of the radionuclides in body tissues or organs. For ^{40}K, metabolic balance maintains body levels irrespective of intake amounts. For uranium- and thorium- series radionuclides, however, this is not the case, and the concentrations in foods, water and total diet have been useful for determining geographic variations in the body burdens.

118. Beginning with the UNSCEAR 1993 Report [U3], representative dietary intakes of natural radionuclides were compiled; these could be used with age-dependent estimates of dose per unit intake to extend the limited data on tissue concentrations and to obtain more broadly based dose estimates.

119. Estimates of dose per unit intake of radionuclides are provided by the ICRP [I5]. These are the committed effective doses to age 70 years, based on recent metabolic data and models. The values used in UNSCEAR assessments are summarized in Table 20. The age categories are infants (1–2 years), children (>7 years to 12 years), and adult (>17 years). Values for age categories from 0 to 1 year, >2 years to 7 years, and >12 years to 17 years are also provided by ICRP [I5].

B. RADIONUCLIDES RELEASED TO THE TERRESTRIAL ENVIRONMENT

120. An extensive database of deposition and diet measurements from the years when there was atmospheric testing has allowed empirical relationships to be derived to evaluate transfer coefficients for radionuclides released in this practice. Empirical models describing the time course of annual transfers from deposition to diet and from diet to the body have been the basis of the Committee's evaluations of doses from ^{90}Sr and ^{137}Cs, and this method was also applied to transuranic radionuclides. Fewer data have been available from which to derive ingestion pathway transfer coefficients for ^{131}I, ^{140}Ba, ^{89}Sr and ^{55}Fe.

1. Transfer processes

121. Plants are the primary recipients of radioactive contamination to the food chain following atmospheric releases of radionuclides. Vegetation may be subject to direct and indirect contamination. The direct contamination of terrestrial vegetation refers to the deposition of radioactive materials from the atmosphere onto the above-ground parts of plants. Indirect contamination refers to the sorption of radionuclides from the soil by the root system of plants. Secondary recipients of food chain contamination are animals that consume plants or other animals. Both plant and animal products enter the diet of humans.

(a) Direct deposition on plants

122. Direct deposition on plants may play an important role in the contamination of plant products for some radionuclides, including those characterized by low root uptake and short-lived radionuclides, especially ^{131}I, that can transfer relatively rapidly through the food chain. The direct contamination of plants may be of two types: primary, which involves direct transfer from the source via the atmosphere to the plants, and secondary, by which activity already deposited on the ground may be resuspended, e.g. by the wind, and thus transferred to the plants. The resuspension process is not usually a substantial factor, except for radionuclides with very small uptake through the roots. Primary direct deposition involves three processes: deposition, interception and retention. Direct contamination of the plants depends on the development stage of the plants at the time of contamination. This, in turn, depends on the season of the year when the contamination occurs.

123. Radionuclides in the atmosphere may be deposited as either dry or as wet deposition. Dry deposition occurs continuously, while wet deposition occurs when rain or some other form of precipitation intervenes. Dry deposition is usually described by applying the deposition velocity, v_g = F/C [C1], where F is the fallout rate of the depositing radionuclide to a unit area of land (Bq m^{-2} s^{-1}), and C is the concentration in ground-level air over the area of land considered (Bq m^{-3}). The unit of v_g is thus m s^{-1}. The deposition velocity varies with the aerodynamic diameter of the particles deposited. Particles with a diameter between 0.1 and 1 μm have a deposition velocity of about 0.02 cm s^{-1}; those between 1 and 10 μm have values ranging from 0.02 to about 5 cm s^{-1} [H1]. This magnitude also varies with the type of surface and with the chemical and physical characteristics of the radioelements involved.

124. Wet deposition occurs during precipitation. The wash-out ratio, W, is defined as the ratio of the radionuclide concentrations in precipitation (Bq l^{-1}) and in ground-level air (Bq m^{-3}) [E3]. Experience from global fallout studies has shown that around 90% of the total deposition of ^{90}Sr and ^{137}Cs occurs as wet deposition. In an accident, most of the deposition usually takes place within a few days. The Chernobyl accident demonstrated that high rainfall during the cloud passage results in deposition rates an order of magnitude higher than those observed for dry conditions [E5].

125. Interception is the fractional deposition of radionuclides on the plant surfaces. It depends on both the physical characteristics of the deposit and the growth form of the plants. The subsequent fate of the deposit, i.e. the

retention, is influenced by these factors and by the rate at which the material is removed by precipitation and other processes, called weathering or field loss.

126. The fraction of material intercepted by the crop canopy was studied by Chamberlain [C2], who derived an empirical parameter dependent on the physico-chemical properties of the deposit, the manner of deposition, the morphology of the crop and the meteorological conditions. The quotient of the fraction retained and the dry weight biomass usually falls within the range 0.2–4 $m^2\ kg^{-1}$ [C3]. The normalized specific activity is defined as the concentration in the crop (Bq kg^{-1} dry weight) divided by the deposition density rate (Bq $d^{-1}\ m^{-2}$) [C2]. The normalized specific activity is thus a rate factor with the unit $m^2\ kg^{-1}$ d. Values between 20 and 40 $m^2\ kg^{-1}$ d have been observed for ^{137}Cs and ^{90}Sr for herbage in good growing conditions [E4]. Chamberlain found that winter grass had normalized specific-activity values 2–3 times higher than summer grass.

127. The weathering or field loss is expressed by $M/M_0 = e^{-t/\tau}$, where M_0 and M are the quantities retained on the crop initially and after time t and τ is an empirical constant. During the growing season, τ is about two weeks; in the winter period, it increases to about eight weeks. When there is rain, the field half-time may be short.

128. Resuspension of radionuclides on the soil surface may result in secondary direct contamination of the crops. The resuspension factor RF is defined as the radionuclide concentration in air (Bq m^{-3}) divided by the ground contamination (Bq m^{-2}). The resuspension factor thus has the unit m^{-1}. The resuspension factor measured at locations in Denmark for 100–3,000 days after the Chernobyl accident decreased according to a power function of the time, t, in days ($RF = 9.3\ 10^{-6}\ t^{-1.17}$) [A3].

129. It appears that resuspended ^{137}Cs is less available to the plant than primarily deposited amounts [A1], i.e. the transfer factor for primary direct contamination is higher than that for secondary direct contamination. There may be two reasons for the lower availability of resuspended particles compared with directly deposited fallout. First, a higher field loss can be expected for resuspended particles than for global fallout. Secondly, ^{137}Cs adheres to minerals, especially clay, allowing the radiocaesium to be less available for absorption by the crops and thus for translocation to the grain.

130. A special case of secondary direct contamination of crops is rain splash, which may occur during heavy showers, when the recoil from rain drops carries contaminated soil to the surface of the vegetation. Secondary contamination is expected to be less efficient with respect to translocation to the plants than the initial, direct contamination route.

131. Seasonal variation in direct contamination is of particular importance for cereals. This feature was first studied by Middleton [M2]. It appears that the two important factors influencing contamination of grain are the initial retention and the translocation from the vegetative part of the seeds. Initial retention is largely independent of the radionuclide, whereas translocation depends strongly on the radioelement and its solubility.

132. Time of year was observed to affect the transfer factor of ^{137}Cs to grain at the time of the Chernobyl accident [U4]. Transfer factors were higher in southern Europe, where the crops were more developed when the deposition from Chernobyl occurred than in northern Europe, where the growth of crops had not yet begun. Seasonality also affected total diet intakes.

(b) Root uptake

133. In the first period after a radioactive contamination event, direct deposition on plant surfaces is the dominant pathway, but in the long term, the contamination of the human diet will depend on absorption through the roots of plants. The extent to which plant roots absorb radionuclides from the soil depends not only on their physiology but also on processes in the soil.

134. The uptake of radionuclides by plants from the soil is normally described by the transfer factor B_v, the ratio of radionuclide concentrations in vegetation and soil (Bq kg^{-1} dry weight plant to Bq kg^{-1} dry weight soil). Observed values of B_v vary widely, mainly as a result of different soil and vegetation types and environmental conditions. In addition, management practices such as ploughing, liming, fertilization and irrigation greatly affect uptake. Variability can also result if uptake into the whole plant is compared with uptake into parts of the plant, such as grain. The transfer factor B_v is not constant in time. Decreases occur as radionuclides in soil become less available to plants through changes in physical or chemical forms or in moving below the rooting zone. In some cases, the rate of uptake increases in time, when physical weathering or transformation of the chemical form takes place or when the radionuclide reaches an optimum depth for root uptake. Databases for root uptake transfer parameters have been published [I9, N7].

135. The main soil characteristics affecting the transfer of radionuclides from soil to plants through root uptake are: clay and organic matter content, pH and cation exchange capacity. These soil characteristics interact causing variability in the transfer in different circumstances, so that generalizations are not always valid. A high clay content in the soil provides binding for caesium and reduces root uptake. A high organic matter content often enhances the root uptake of caesium but may also have the opposite effect; an excess of potassium dilutes caesium ions, which decreases uptake, but may also cause the desorption of fixed caesium, which increases uptake.

136. The root uptake of ^{137}Cs usually decreases with time, in the beginning quite rapidly, later more slowly. The

decrease is seen particularly in clay soils and is due to the fixation of caesium by clay minerals such as illite and vermiculite. In organic soils the decrease is mainly due to redistribution of caesium within and transport out of the rooting zone. Strontium is less firmly fixed to the soil matrix and is thus more available for root uptake than caesium. The higher mobility of ^{90}Sr also means that this radionuclide migrates faster than ^{137}Cs through the soil column. Nevertheless, root uptake of ^{90}Sr generally remains significantly greater than that of ^{137}Cs over periods of several years, and for terrestrially produced foods a generally increasing ^{90}Sr/^{137}Cs ratio will occur with time after deposition.

137. Under special circumstances the root uptake, especially of ^{90}Sr, may increase with time after contamination. This has been observed, for example, in the near zone around the Chernobyl reactor where some of the ^{90}Sr was imbedded in uranium fuel particles. Weathering throughout the years has dissolved these fuel particles, making the ^{90}Sr available for delayed root uptake by plants.

(c) Animal pathways

138. Several important pathways for the transfer of radionuclides to the diet of humans involve animal food chains, including milk and eggs from living animals and meat or flesh from animals and fish. Depending on the radionuclide and the metabolism in the organism, the concentrations may be enhanced or reduced compared with the earlier steps of the food chain. Some parts of the animal are not consumed, e.g. bones, shells, skin and feathers, and this prevents the transfer from animal products of bone-seeking radionuclides such as ^{90}Sr and plutonium. Bone tissue might, however, re-enter the food chain as bonemeal in various fodder products, and it might also appear in fertilizers.

139. The main animal pathway to humans of the radiologically important radionuclides such as ^{90}Sr, ^{131}I and ^{137}Cs is milk consumption. All three radionuclides are readily transferred from animal fodder to the milk. Other radionuclides such as the transuranic elements are absent or secreted to only a very small extent in milk. Caesium is transferred with its chemical congener potassium to the soft tissues of animals, particularly muscle. Strontium is preferentially transferred to bone, like its congener calcium.

140. Fish and shellfish receive radionuclides both directly from the water and from their food. Some radionuclides that are of no concern in the terrestrial animal food chains may be concentrated in aquatic animals. This is the case, for example, for plutonium, which is concentrated in crustaceans, and for polonium in fish and seafood. A substantial part of the marine fish catch is used for making fishmeal, which is used as fodder for pigs and poultry and for fish produced in fish farms. In this way, marine pathways may interact with terrestrial and freshwater animal food chains.

(d) Losses in food preparation

141. Knowledge of the effects of processing and culinary preparation on radionuclide contents in foods is needed when assessing the radiation dose to humans from the ingestion of contaminated foodstuffs. Appropriate allowances might be made for the reductions brought about by food processing to ensure that doses are not systematically overestimated [N1]. However, the Committee has not specifically considered this for its calculations. In some cases, losses via food processing are considered implicitly, if the assessment is based upon nuclide content in people.

142. Food-processing retention factors, i.e. the fractional amount of the radionuclide remaining in the food after processing, are quite variable, depending on the food and the processing procedure. Drying foods increases the concentrations in the dried products, typically by a factor of 5 compared with the fresh foods. Boiling meat considerably reduces the radionuclide content. It should, however, be kept in mind that some of the water used for the boiling may be consumed as soup or sauce. In dairy products, radionuclides are retained less in cream, thus affecting the levels in various milk products. Radionuclide contents in vegetables and fruits are also significantly affected by washing, peeling, and cooking. In particular, the reduction of ^{137}Cs by various treatments is significant. If crops have been contaminated only by direct deposition, the effect of washing and peeling will be even higher, because the contamination in that case is confined to the outer parts of the crops. Some translocation may eventually take place.

143. The process of milling cereal grains apportions the radionuclide content of the whole grain to significantly lower radionuclide concentrations in the flour and correspondingly higher concentrations in the bran. The intakes of ^{137}Cs and particularly ^{90}Sr are thus higher for consumers of wholemeal bread than for consumers of white bread. The concentrations of ^{90}Sr and ^{137}Cs in white bread are 20% and 40% of the concentrations in the wheat, respectively. In rye bread, the percentage is 75% of that in the grain for both radionuclides. There is essentially no transfer of ^{90}Sr or ^{137}Cs to alcohol from grain or potatoes nor to sugar made from beets.

144. Conversion of foods, e.g. milk to cheese, may also change the radionuclide concentrations. The concentration of ^{90}Sr in cheese is thus typically 5–10 times higher than in milk, while the concentration of ^{137}Cs in normal cheese is only about 70% of that in milk. Butter contains essentially none of the ^{90}Sr and ^{137}Cs present in the milk.

145. Assessments by UNSCEAR have not specifically accounted for losses in food preparation. Rather, it has been assumed that dietary intake estimates reflect actual amounts in prepared and consumed foods. When it appears that this is not the case, the intake estimates will need to be adjusted.

(e) Behaviour of tritium and carbon-14

146. The radionuclides tritium and ^{14}C require special consideration because of their high mobility in the environment and the fundamental nature of hydrogen and carbon cycles in the biosphere.

147. Carbon is highly mobile and is distributed throughout the environment. A small fractionation effect reduces environmental concentrations of ^{14}C by about 5% relative to stable ^{12}C, but this difference is usually disregarded in the models. Carbon-14 released into the environment via the atmosphere enters the carbon cycle and becomes dispersed in the atmosphere, terrestrial biosphere, and more gradually into the ocean, ocean sediment and sedimentary rocks. Much of the carbon in plants has a short residence time, although carbon is held longer in woody plant parts and is released only on decomposition. Turnover time of carbon in humans is generally of the order of a few days or weeks. The most important form of carbon from the point of view of dose is CO_2, since this is the form in which carbon becomes bound in plants and ingestion contributes 99% of the dose from ^{14}C. The remaining fraction of dose comes from inhalation of ^{14}C in air.

148. Tritium released to the atmosphere occurs in two forms: tritiated hydrogen (HT) and tritiated water vapour (HTO). HTO is subject to the same wet and dry deposition processes as other nuclides, but it can also diffuse into the soil pore space and the leaf stomates [B7, G1]. If the HTO gradient is reversed, however, (for example, if a wind shift blows the plume away), tritium will rapidly be lost from the soil and plants to the atmosphere by evaporation and transpiration, generating a secondary airborne HTO plume. HT can diffuse into the soil and be converted to HTO by an enzyme-mediated reaction [D2, T2]. Tritium not returned to the atmosphere by evaporation moves through the soil primarily by the mass flow of liquid water.

149. Like other radionuclides, tritium enters plants via root uptake. Under steady conditions, the concentration in the plant lies between the concentrations in the soil and the air, with a magnitude that depends on atmospheric humidity and the air/leaf temperature difference [M4]. Some of the tritium that enters plants can be incorporated into organic compounds to form organically bound tritium (OBT) [D3]. Tritium bonded to carbon forms non-exchangeable OBT, which has a much longer retention time in plants and animals than HTO and so can contribute significantly to the total dose. Organically bound tritium makes up only a small percentage of the total tritium activity in most plants, but up to 90% in grains, which have a high organic content.

150. Tritium is taken into the bodies of animals (including humans) by the normal mechanisms, and HTO equilibrates with body fluids within minutes. For the most part, the retention time of tritium in the body is about 10 days, although for the organically bound form it increases to about 40 days [T3].

2. Food and water consumption

151. The consumption of foods and water by individuals varies widely around the world, depending on climate, food availability and cultural dietary preferences. Locally produced or gathered foods are now usually greatly supplemented by foods imported from other regions or countries. Moreover, it is difficult to obtain accurate estimates of food consumption: there are considerable individual variations, and many foods are of a seasonal nature. Average rates in countries may be indicated by food balance analysis, taking into account local production, imports, and exports [F1]. These will be overestimates, however, if losses from wastage or preparation are not taken into account.

152. When UNSCEAR has needed dietary intake information, it has used values reported from a few countries. For example, the analysis of fallout ^{90}Sr transfer to humans was based on measurements in Argentina, Denmark, and New York City. For lack of more extensive data, these results were averaged and assumed to be generally applicable. Milk consumption has been reported for many other locations. For general assessment purposes, the Committee has used an average dietary intake of 500 kg a^{-1}.

153. For the analysis of exposures following the Chernobyl accident, the Committee compiled consumption data for all countries reporting first-year measurements. These values were as assessed by scientists of the various countries or, secondarily, derived from food balance considerations. The consumption rates, as given in the UNSCEAR 1988 Report [U4], are listed in Table 21. This listing is relatively extensive, allowing regionally relevant estimates to be derived. Some variations within geographic regions are fairly wide. Some of these differences might be explained by local habits. Other differences may result from inconsistencies in the definitions of the food categories, especially for leafy and other vegetables. Population-weighted average values from this listing [U4] are given in Table 21. These may be taken to be reasonable representative for very broad geographic regions. Changing dietary habits, however, require such food consumption data to be periodically updated.

154. Although many regional differences in consumption can be noted, the data seem to separate only very broadly into western and eastern countries. The western diet contains greater amounts of dairy products and meat. These foods are replaced by grain products, vegetables, and fish in Asian countries. The average value of consumption for the world would not apply to any individual and could only be used in some generic dose assessments. The consumption rates of children are less well known. In the UNSCEAR 1993 Report [U3], milk consumption was assumed to be 120 kg a^{-1} for infants and 110 kg a^{-1} for children. Other foods were assumed to be consumed at the rate of two thirds (children) or one third (infants) of the

adult values [C5]. This gives consistent and reasonable values to be used in dose assessments (see Table 13 of Annex B, "*Exposures from natural radiation sources*").

155. Drinking water intake has been estimated for reference individuals. For both water and beverages, the estimates are 500 l a^{-1} for adults, 350 l a^{-1} for children and 150 l a^{-1} for infants [I7]. Since the water balance is affected by ambient temperatures, regional estimates of these quantities should be established, if possible.

156. The consumption of foods from semi-natural and natural ecosystems, such as mushrooms and game, varies widely and is, in general, poorly known. Although these foods may comprise only a few percent (5–10 kg a^{-1}) of an individual's total annual dietary intake, such intake could be important for some radionuclides in certain times and places such as the arctic food chain (lichen-caribou/ reindeer-human) for both natural and fallout radionuclides and for consumers of game and forest mushrooms and berries for ^{137}Cs following the Chernobyl accident. Usually only a very small portion of a country's population will be significantly affected, so collective dose estimates are little modified. For further analyses of these situations, better data on the consumption of these foods are needed.

3. Methods for estimating exposures

(a) Atmospheric nuclear testing

157. To make reliable assessments of doses through the ingestion pathway of radionuclides released in atmospheric nuclear testing, extensive empirical data were compiled on the concentrations of the relevant radionuclides in different types of food and the diets of different population groups. The data were analysed in previous reports of the Committee, especially for ^{90}Sr and ^{137}Cs, which together with ^{14}C, are the main contributors to the ingestion dose commitments from this practice [U6, U7]. To evaluate the transfer coefficients, regression analyses were applied to models relating measured radionuclide concentrations in diet to the annual deposition density rates and the measured concentrations in relevant organs. Information on diet and deposition levels of other radionuclides are incomplete, so the P_{23} coefficients estimated for such radionuclides are less reliable than those available for ^{90}Sr and ^{137}Cs.

158. The empirical model used to relate the deposition density of a radionuclide, specifically ^{90}Sr or ^{137}Cs, to the integrated concentration in components of the diet or in total diet is the following

$$C_i = b_1 \dot{F}_i + b_2 \dot{F}_{i-1} + b_3 \sum_{n=1}^{\infty} e^{-\lambda n} \dot{F}_{i-n} \qquad (27)$$

where C_i is the concentration of the radionuclide in a food component or in the total diet in the year i due to the deposition density rate in the year i, F_i, in the previous year, F_{i-1}, and in all previous years, reduced by exponential decay. The exponential decay with decay constant λ reflects both radioactive decay and environmental loss of the radionuclide. The coefficients b_i and the parameter λ are determined by regression analysis of measured deposition and diet data.

159. The transfer coefficient from deposition to diet is given by

$$P_{23} = \int_0^{\infty} C(t)\,dt \;/\; \int_0^{\infty} \dot{F}(t)\,dt \quad \text{or} \quad \sum_{i=1}^{\infty} C_i / \sum_{i-1}^{\infty} \dot{F}_i \qquad (28)$$

From the above model, the transfer coefficient can be expressed as

$$P_{23} = b_1 + b_2 + b_3 e^{-\lambda m}/(1 - e^{-\lambda m}) \qquad (29)$$

where b_i are the transfer components per unit annual deposition: b_1 is the transfer in the first year, primarily from direct deposition; b_2 is the transfer in the second year from lagged use of stored foods and uptake from the surface deposit; and b_3 is the transfer via root uptake from the accumulated deposit. The units of P_{23} and b_i are Bq a kg^{-1} per Bq m^{-2}. In the exponential term, the unit for λ is a^{-1} and m is a constant equal to one year. The values of the parameters used are given in Table 22.

160. Results of regression fitting of this fallout model to monitoring data were presented in previous UNSCEAR Reports [U6, U7, U8]. Relatively minor adjustments in parameter values were needed in the fits to extended monitoring data, indicating, in particular, that the projections of long-term transfers are confirmed.

161. Adequate representations of transfers to the total diet or to separate components of the diet are obtained for relatively uniform deposition during the year, as occurred for fallout from atmospheric weapons testing. For deposition occurring within a much shorter time period, such as following the Chernobyl accident, the transfer is dependent on the particular agricultural conditions at the time of deposition and on short-term restrictions on certain foods in the diet that may have been imposed.

162. If P_{23} is multiplied by the individual annual consumption of food (kg a^{-1}), the transfer coefficient P_{24}, which relates to the intake of the radionuclide, is obtained. The transfer coefficients P_{45} then relate the intake amount to the dose (Sv Bq^{-1}). This is a committed dose that accounts for longer-term retention of the radionuclide in the body.

163. The Committee's earlier evaluations of transfer coefficients related the integrated concentration of the radionuclide in the body to the dose [U6]. For ^{90}Sr, the empirical relationship was as follows:

$$C_{b,i} = c\,C_{d,i} + g \sum_{m=0}^{\infty} e^{-\lambda_b m} C_{d,i-m} \qquad (30)$$

where $C_{b,i}$ and $C_{d,i}$ are the concentrations of ^{90}Sr in bone and diet in the year i and the parameters c and g may be related to short- and longer-term components of ^{90}Sr retention in bone. The exponential term accounts for radioactive decay and removal from the body. Average values derived for the parameters are listed in Table 22. This formulation is useful for determining the annual components of dose from a specific deposition occurrence.

164. The results of transfer coefficient evaluations for a number of radionuclides are listed in Table 23. For ^{90}Sr and ^{137}Cs, the values are the same as those previously derived [U3]. It should be stressed that the transfer coefficients P_{23}, P_{234} and P_{2345} are all calculated for an even distribution of the deposition throughout the year, as was the case for global fallout from atmospheric nuclear testing. If the deposition occurs during the winter season, the transfer coefficients are lower, and for a summer deposition they are higher than the value for the even distribution.

165. The transuranic radionuclides considered by the Committee in dose evaluation from atmospheric testing were ^{238}Pu, ^{239}Pu, ^{240}Pu and ^{241}Pu together with its decay product ^{241}Am. The empirical model described above, equation (27), has been used to relate the deposition amount to the integrated levels in diet. The lag term, however, was not included ($b_2 = 0$).

166. As the number of measurements of the annual ingestion intake, I_{ig}, of plutonium radionuclides were very few and covered only 11 years, the determination of λ is very uncertain; large variations in the value of λ result in only small variations in the value of I_{ig}. Taking λ to be very small, Bennett [B2] found the average solutions for b_1 and b_3 to be $3.3\ 10^{-2}$ Bq per Bq m^{-2} and $3.5\ 10^{-4}$ Bq per Bq m^{-2}, respectively, for $^{239,240}Pu$. The estimation of P_{234} depends on the real value of λ. It could be as low as $5\ 10^{-2}$ Bq per Bq m^{-2} if the availability of plutonium decreases with a mean residence time of 50 years ($\lambda = 0.02\ a^{-1}$) and as high as about 10 Bq per Bq m^{-2} for ^{239}Pu and 3 Bq per Bq m^{-2} for ^{240}Pu, if the availability of plutonium decreased only as a result of radioactive decay ($\lambda = 3\ 10^{-5}\ a^{-1}$ and $1\ 10^{-4}\ a^{-1}$). Aarkrog [A4] estimated the transfer of $^{239,240}Pu$ to bread, an important component of diet, to be $2\ 10^{-2}$ Bq per Bq m^{-2}. Until additional information becomes available, the geometric mean of the extremes for transfer to total diet can be assumed for the transfer coefficient P_{234}, namely, 0.7 Bq per Bq m^{-2}. This result corresponds to a mean residence time of $^{239,240}Pu$ in soil of about 100 years, the value that was also adopted in Annex C of the UNSCEAR 1982 Report [U6] for the mean residence time in soil of long-lived natural radionuclides released from industrial plants.

167. For ^{238}Pu, the above estimate of P_{234} using the 50–year residence time in soil is appropriate, considering the similar radioactive half-life of this isotope. Given the short half-life of ^{241}Pu (14.4 a), the value of P_{234} is dominated by the rate effect and is taken to be equal to $4\ 10^{-2}$ Bq per Bq m^{-2}. In the case of ^{241}Am, the formulation is complicated by the need to take the decay of ^{241}Pu into account. Using the equivalent of equation (29) and taking λ_s to be very small and b_1 to have the same value as that obtained for $^{239,240}Pu$, Bennett [B11] estimated b_3 to be equal to $8\ 10^{-4}$ Bq per Bq m^{-2}. This value is very uncertain, as only one measurement of the annual dietary intake of ^{241}Am has been reported, but it points to the possibility that americium contained in the soil may be slightly more available to plants than plutonium. The value of P_{234} can be roughly assessed to range from $6\ 10^{-2}$ Bq per Bq m^{-2} for a residence time of ^{241}Am in soil of 50 years to 0.7 Bq per Bq m^{-2} if the availability of ^{241}Am decreases only by radioactive decay. The geometric mean of this range is 0.2 Bq per Bq m^{-2}.

168. The estimated values of the transfer coefficients for the transuranic radionuclides are listed in Table 23. These estimates are about 20 times higher than those used previously by the Committee because of the higher values of the dose factors that have since been recommended by ICRP. The total dose from plutonium will, however, not be influenced by this change because the dominating pathway for plutonium is inhalation, and here the dose factors are reduced by a factor of 4 (for class Y = type S). The transfer coefficients for ^{241}Am are also listed in Table 23.

169. Curium is chemically very similar to americium, and it may be assumed that the transfer coefficients for the various curium isotopes can be calculated as for ^{241}Am, taking the half-lives of the curium isotopes into consideration. Curium-244, which has a half-life of 18.1 years, can thus be assumed to have a P_{234} coefficient equal to 0.04 Bq per Bq m^{-2} and with the dose factor $1.2\ 10^{-7}$ Sv Bq^{-1}, P_{2345} is estimated to be 5 nSv per Bq m^{-2}.

170. Less complete data are available for deriving transfer coefficients for ^{131}I, ^{140}Ba and ^{55}Fe. Radioiodine can be transferred rather quickly via the pasture–cow–milk chain to humans. Hence, although ^{131}I is a short-lived radionuclide (half-life: 8 days), it may contribute significantly to the dose in the first weeks after a release. P_{234} for ^{131}I was calculated to be 0.07 Bq per Bq m^{-2} from a P_{23} coefficient for milk of 0.63 mBq a l^{-1} per Bq m^{-2} and an average milk consumption rate of 0.3 l d^{-1}. The dose factor for ^{131}I ingestion by adults is $2.2\ 10^{-8}$ Sv Bq^{-1}, so P_{25} becomes 1.5 nSv per Bq m^{-2} for ^{131}I. For the age group 0–1 year, daily milk consumption is 0.9 l and the dose factor is $1.8\ 10^{-7}$ Sv Bq^{-1}, so in this case P_{25} becomes 37 nSv per Bq m^{-2}. A weighted average of P_{25} for all age groups for ingestion is 4.3 nSv per Bq m^{-2} for ^{131}I. Similar considerations were applied for ^{140}Ba. The estimates are included in Table 23.

171. The transfer coefficient P_{234} for ^{55}Fe was estimated in the UNSCEAR 1993 Report [U3] to be 10 Bq per Bq m^{-2}. For adults, P_{45} is 3.3 10^{-10} Sv Bq^{-1} for ^{55}Fe, and P_{2345} for the ingestion of ^{55}Fe becomes 3 nSv per Bq m^{-2}. It should be noted that P_{234} for ^{55}Fe also includes a contribution from consumption of fish, which are known to concentrate ^{55}Fe from seawater [I10]. Hence P_{234} for ^{55}Fe in the terrestrial environment is overestimated. Values of 6 Bq per Bq m^{-2} for P_{234} and 2 nSv per Bq m^{-2} for P_{2345}, assumed applicable for terrestrial pathways, have been inserted in Table 23.

172. Although not previously considered in exposure evaluations from ingestion, some limited data may be used to derive rough estimates of transfer coefficients for ^{54}Mn and ^{144}Ce. From measurements of ^{54}Mn in grain in 1962–1966 in localized areas in the northern hemisphere [A5], the transfer coefficient from deposition density to concentration in grain was estimated to be 0.025 Bq a kg^{-1} per Bq m^{-2}. Assuming an annual consumption of grain products of 80 kg and that all ^{54}Mn in the diet comes from grain products, P_{234} becomes 2 Bq per Bq m^{-2}. For adults, P_{45} is 7.1 10^{-10} Sv Bq^{-1} for ^{54}Mn, and P_{2345} for ingestion of ^{54}Mn becomes 1.4 nSv per Bq m^{-2}.

173. Cerium is relatively unavailable to plants. Assuming that a first-term component similar to that of plutonium applies and that there are no other terms because of the short half-life of ^{144}Ce, the transfer coefficient P_{234} would have the value 0.1 Bq per Bq m^{-2}. The further transfer coefficients have been added in Table 23.

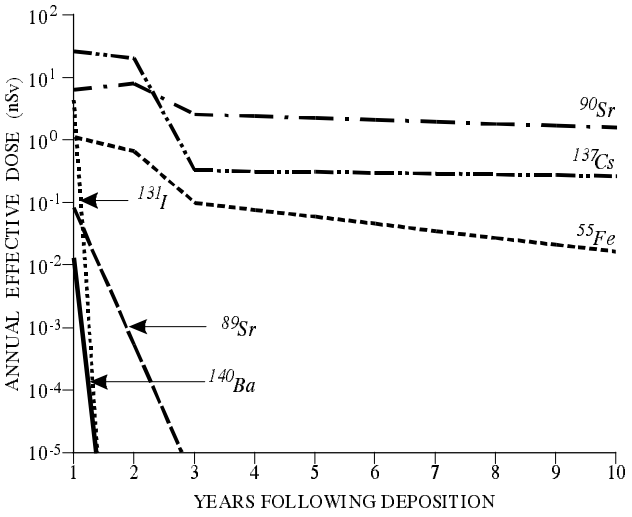

Figure IV. Ingestion exposure following unit deposition (1 Bq m^{-2}) of radionuclides.

174. The above analyses have been made to derive dose commitments per unit deposition density, but annual values of contributions to dose from a single deposition event may be useful and can also be provided. These values are given in Table 24. Because of the short half-lives of ^{131}I and ^{140}Ba, the dose is delivered within a few weeks of deposition and for ^{89}Sr, within a few months. All of the dose is delivered within one year of the deposition. There is no model for the transfer of ^{55}Fe to diet, but an approximation may be made on the pattern of transfer of longer-lived radionuclides to diet, namely significant transfer within the first two years following deposition and residual transfer over the remaining mean life of the radionuclide (see footnote to Table 24). The empirical models for ^{90}Sr and ^{137}Cs provide the time course of transfer to dose for annual periods following deposition of these radionuclides. The annual contributions to dose from ingestion for a period of 10 years following deposition are illustrated in Figure IV. The contributions beyond 10 years, which are significant only for ^{90}Sr and ^{137}Cs, are given in Table 24. The total of all annual contributions is equal to the dose commitment.

(b) Nuclear installations

175. Radionuclides released to the atmosphere from nuclear installations may contribute to exposures from ingestion in the local and regional areas surrounding the site. The concentrations of the radionuclides in the environment and the doses are too low to be measured, but they can be estimated with calculational methods.

176. The dispersion estimation method described in Section I.B.3 and applied to the external exposure pathway is also applicable to ingestion exposure, substituting in equation (24) the P_{25} transfer coefficients for ingestion intake. A more specific designation of the ingestion transfer coefficients is P_{2345}. The values in Table 23 are applicable also to the case of routine continuous or long-term averaged releases of radionuclides from nuclear installations. Several additional radionuclides not normally included in analysis of weapons fallout but present in releases from nuclear installations such as ^{59}Fe, ^{58}Co, ^{60}Co and ^{134}Cs have been added to Table 23.

177. The estimates of local and regional collective dose from ingestion per unit release of radionuclides from nuclear installations are presented in Table 25. The results should be adjusted if it is known that some portion of the diet is derived from non-local foods. Also the representative population density may not apply to specific sites. The representative values of population densities for various steps of the fuel cycle are given in Table 26.

178. Specific values given in Table 25 of the collective dose per unit release are needed in exposure evaluations for releases from separate fuel cycle installations. For the general category of particulates released from reactors, a representative composition may be assumed (see paragraph 96). The weighted average collective doses from ingestion per unit release of particulates are included in Table 25. Of course, the specific radionuclide weightings should be adjusted, if the exact composition of the release is known.

179. An alternative method, the specific-activity approach, is used to estimate doses from tritium and ^{14}C. In this approach the specific activity of ^{14}C, for example, in ingested food and water (activity per gram carbon) is assumed to be the same as the activity per gram carbon in

air at the point of interest. This is a good approximation for situations where rapid exchange occurs, such as between atmosphere and terrestrial biota, and the specific-activity model provides a good estimate of ^{14}C doses for chronic releases from nuclear facilities. However, it is necessary to know the carbon content of plants and animals to apply this approach rigorously. The specific activity in air is reflected in humans after about one year.

180. The specific-activity model for tritium is expressed in terms of the tritium to hydrogen atom ratio. For aqueous compartments (air moisture, plant water, soil water and so on), the constancy of this ratio is equivalent to assuming that the HTO concentration in Bq l^{-1} is constant. However, a strict specific-activity approach overestimates doses for tritium, since it assumes a level of equilibrium between tritium in the environment and in the atmosphere that is rarely achieved. Concentrations in precipitation, and therefore in soil, are lower than those in air, because the airborne plume is not always present when precipitation occurs. Concentrations in plants will be lower than those in air by an amount that depends on the transpiration rate. Concentrations in drinking water tend to be much less than air concentrations because of the large dilution that occurs in most drinking water sources. Concentrations in animals and humans reflect the concentrations in the food products and drinking water they ingest.

181. The general formula for the specific-activity approach to evaluate the collective dose is as follows:

$$S_i = \frac{5\,10^{-7}\ s\ m^{-3}}{3.15\ 10^{7}\ s\ a^{-1}} \frac{I_{g,n}}{C_{a,n}}\ d_{g,i} \left[N_1 \int_1^{50} x^{-1.4}\, 2\pi x\, dx + N_2 \int_{50}^{2000} x^{-1.4}\, 2\pi x\, dx \right] \quad (31)$$

where $I_{g,n}$ is the ingestion intake rate of the stable form of element n (kg a^{-1}); $C_{a,n}$ is the concentration of the stable form of element n in air (kg m^{-3}); $d_{g,i}$ is the effective dose per unit intake by ingestion of radionuclide i (Sv Bq^{-1}); and N_1 and N_2 are the population densities in the local and regional areas. For tritium, the exponent in the power function of distance should take the value 1.2 rather than 1.4 because of less local retention of deposited tritium.

(i) Tritium

182. Application of equation (31) for tritium requires estimates of the intake rates of both water-bound and organically bound hydrogen in foods and drinking water. To account for the fact that tritium concentrations in the various foodstuffs ingested are lower than the concentrations in moisture in air, $I_{g,n}$ is determined as follows:

$$I_{g,n} = \sum_i f_i U_i \quad (32)$$

where U_i is the intake rate of hydrogen from ingestion of food type i and f_i is the ratio of tritium concentration in food type i to the concentration in moisture in air.

183. Representative intake rates of plant foods, animal foods, and drinking water may be assumed to be 370, 170, and 500 kg a^{-1}, respectively. With typical water content of plant foods of 85% and of animal foods of 78% [D6] and the hydrogen content of water being 11.1%, the intake rates, U_i, of water-bound hydrogen are 35 kg a^{-1} in plant foods (370 × 0.85 × 0.111), 15 kg a^{-1} in animal foods (170 × 0.78 × 0.111), and 56 kg a^{-1} in drinking water (500 × 0.111).

184. In the organic matter of foods, the hydrogen content is, on average, 5.8% in plant foods and 8.4% in animal foods [D6]. The intake rates, U_i, of organically bound hydrogen are thus 3.2 kg a^{-1} in plant foods (370 × 0.15 × 0.058) and 3.1 kg a^{-1} in animal foods (170 × 0.22 × 0.084).

185. The value of f_i for plant foods is about 0.8 or less [D1, H3, H4, M4]. For drinking water the value of f_i is variable, depending on local conditions. At sites on large water bodies, where tritium enters only from the atmosphere, f_i tends to be less than 0.1 [L2, N6]. Larger values of f_i, even approaching 1.0, might apply to small water bodies, but the low volume or flow rate of such sources would limit the suitability of the site to supply drinking water. Larger values of f_i could also apply to sites downstream of liquid discharges of tritium [N6] or if groundwater had been contaminated. Both of these cases, however, do not pertain to atmospheric releases. For the present calculations, f_i for drinking water is assumed to be 0.1. The value for specific sites should be based on local conditions. For animals, it may be assumed that 40% of water intake is derived from drinking water [R1]. The value of f_i for animal foods is thus estimated to be 0.5 for combined intakes of drinking water and plants (0.4 × 0.1 + 0.6 × 0.8).

186. It will be assumed that the concentration of organically bound tritium (Bq l^{-1} water equivalent) is the same as the concentration of water-bound tritium in both plants and animals so that the same values of f_i apply to the aqueous and organic phases. The value of $I_{g,n}$ is then estimated to be 40 kg a^{-1} in water-bound form (0.8 × 35 + 0.5 × 15 + 0.1 × 56) and 4 kg a^{-1} in organically bound form (0.8 × 3.2 + 0.5 × 3.1).

187. The annual average content of water vapour in air is assumed to be 8.1 g m^{-3} [U6], implying that C_a for hydrogen is $9\,10^{-4}$ kg m^{-3}. Population densities surrounding the point of release are given above. The dose per unit intake, d_g, was previously taken to be $2.2\ 10^{-11}$ Sv Bq^{-1} for water-bound tritium [U4, U6], but the value now recommended is $1.8\ 10^{-11}$ Sv Bq^{-1} [I5]. The dose coefficient for organically bound tritium is $4.2\ 10^{-11}$ Sv Bq^{-1} [I5]. Applying these parameters in equation (31), recalling that for tritium the exponent in the power function is 1.2, and summing the water- and organically bound doses, the result is 2.1 man Sv PBq^{-1} (local plus regional exposure) (Table 25). The dilution factor and the dose per unit intake are lower than in previous

assessments by the Committee, and the allowance has been made for reduced environmental concentrations relative to moisture in air. These reductions are partially offset by the use of a smaller exponent for the decrease in air concentration with downwind distance and the separate consideration of organically bound tritium. The net result is a dose lower by about a factor of about 4 than the previously derived value of 9 man Sv PBq^{-1} [U4, U6]. Organically bound tritium contributes about 20% of the dose but would contribute more for diets high in grain or rice, which have high organic fractions.

(ii) Carbon-14

188. The dose from local and regional exposure to ^{14}C released to the atmosphere represents only a small proportion of the total dose commitment. The main significance of ^{14}C stems from its global dispersion and entry into the carbon cycle, leading to long-term exposure (see Section V.B). The local and regional collective dose commitment was previously assessed by the Committee using the specific-activity approach. The Committee assumed in its 1982 Report [U6] that the release of ^{14}C is in the form of CO_2 and the concentration of carbon in the atmosphere, C_a, is 0.16 g m^{-3}. A more recent, revised value is 0.18 g m^{-3} [T1]. The intake rate of carbon is 300 g d^{-1} by men and 210 g d^{-1} by women, averaging 93 kg a^{-1} intake by ingestion, I_g. The dose per unit intake of ^{14}C by ingestion is 5.8 10^{-10} Sv Bq^{-1} [I5]; the value formerly used was 5.6 10^{-10} Sv Bq^{-1} [U6]. It is assumed that, unlike tritium, all components of the diet attain the specific-activity level of air at the location of interest downwind from the source. Substituting these parameters into equation (31), the result is 270 man Sv PBq^{-1} (local plus regional exposure) (Table 25).

189. For both tritium and ^{14}C, the approximations of the specific-activity method are recognized. The assumption for ^{14}C that all intake attains the specific activity at the point of calculation is not realistic. For tritium, the concentrations in the environment, although allowed to differ from the concentration in air, are probably overestimates. For both radionuclides, the time distribution in the delivery of the dose must be ignored. The approach thus probably leads to overestimates of the doses. Nevertheless, the method has the advantage of being a simple approach that can be easily adjusted for alternative parameters that might more accurately reflect actual local conditions.

190. Significant doses from a short-term ^{14}C release will be received only in the year of the release. Carbon-14 doses arise only from ingestion and once the food crop of the year of release is consumed, there are no significant pathways for further exposure. Small amounts of ^{14}C deposited in the soil during the release may be re-emitted and taken up by plants, but concentrations would be very low and doses imparted by eating the plants would be insignificant compared with those received in the year of release.

C. RADIONUCLIDES RELEASED TO THE AQUATIC ENVIRONMENT

191. Radioactive contamination of the aquatic environment may result in ingestion doses by three pathways: drinking of freshwater from both surface and ground sources, consumption of biota living in the water, typically fish, and consumption of terrestrial foods that have been contaminated by the use of freshwater for irrigation, by the application of sediments as soil conditioners, or by the application of aquatic plants as fertilizer. Water consumed by animals may also form a pathway for the transfer of radionuclides to the human diet. Shoreline deposits of contaminated sediments can contribute to external exposures.

1. Transfer processes

192. Radioactive material released to the aquatic environment is transported and dispersed by advective and turbulent processes occurring in the water body. Interactions between radionuclides and suspended matter and sediments may remove radionuclides from the solution. It is convenient to consider separate categories of water bodies for modelling the behaviour of radioactive material: lakes, rivers, groundwater, coastal seas, and oceans.

(a) Lakes

193. Contaminants in lakes may occur in solution in the water phase or in the sediments. Most radionuclides occur in both phases, and the distribution factor K_d describes their partition between water and sediments. Lakes receive water from rivers, soil run-off and rainfall and lose water by outflows and evaporization. The mean residence time of the water in a lake depends on this in- and outflux of water to and from the lake. The mean residence time of the radionuclide in the water phase of a lake depends furthermore on the K_d for the radionuclide and its radioactive decay. The water chemistry of the lake (pH, mineral and organic matter content, and redox) influence K_d. These factors also influence the uptake of radionuclides in biota. Lakes that are low in nutrients usually show higher concentration factors from water to biota than nutrient-rich lakes.

(b) Rivers

194. Rivers may be considered as lakes with a high in- and outflux of water. Thus, the mean residence time of radionuclides in water in a river is usually significantly shorter than that in a lake for a similar volume of water, so lower concentrations are usually found in rivers than in lakes for the same input of radionuclides to the two systems. The amounts of water carried by a river may vary considerably throughout the year. In the spring, when the snow melts, the river may cover an area several times that covered in the dry season of the year. The flood land along a river may retain radionuclides carried by the river water,

and this contamination may be released to the river again in subsequent years. Accordingly, it is more complicated to model the behaviour of radionuclides in river systems than in lakes. Sediments in the river bed may, during flooding conditions, also be transported to new locations in the river system and eventually be carried to the sea. Sediments may also be disturbed by dredging and other activities.

(c) Groundwater

195. Lakes and rivers contain 0.3% and 0.003%, respectively, of the total freshwater inventory of the world [U14]. Ice sheets and glaciers contain 75% and groundwater the remaining part, i.e. about one fourth of all freshwater is present as groundwater. Groundwater is, in general, well protected against atmospheric radioactive contamination, because adsorption, chemical precipitation and ion exchange prevent or delay the migration of many radionuclides, such as ^{90}Sr, ^{137}Cs, and ^{239,240}Pu. But some radionuclides, especially those of a noncationic form, e.g. tritium, ^{99}Tc, and ^{129}I are not completely retained by the soil. Tritium in the form of HTO is particularly mobile and is readily measurable in young groundwaters (less than 30 years). Groundwater may be contaminated in connection with underground waste disposal. This has been seen, for instance, at the Hanford site in the United States, where liquid waste has been discharged to the ground, contaminating the groundwater, first of all with tritium. Underground nuclear explosions at, for example, the Nevada test site, contaminated groundwater with tritium [M9]. The contamination of groundwater by long-lived radionuclides may be of interest in connection with the permanent disposal of high-level waste in underground depositories.

(d) Marine waters

196. The total volume of the water in the ocean is $1.37\ 10^{21}$ l [K1], which is four orders of magnitude more water than found in rivers and lakes together. However, most of the water in the ocean belongs to the deep ocean which is not used by man for food production. Fish and other marine foods are mainly produced in the coastal seas, which have a mean depth of about 50 m and a volume of $1.37\ 10^{18}$ l, or 0.1% of the total water volume of the ocean.

197. Some coastal seas are much like closed systems, and the residence time of the water in such systems is relatively long. Other coastal waters have a more direct connection to the open ocean, and the mean residence time there is shorter. In the present context, the North Sea has been taken as a typical coastal sea, and the mean residence time of the water of the North Sea has been taken as representative of all coastal seas.

198. Unlike freshwater systems, where the composition of the water shows great variation, marine waters generally have the same mineral composition. The increase in salinity in the transition from river to sea causes a desorption of radionuclides from sediments. The decreased fixation in estuaries is partly counterbalanced by a lower uptake by biota.

2. Methods for estimating exposures

199. Dose assessments for radionuclides released to the aquatic environment require, in general, information on the activity of each radionuclide released, the volume of the receiving water into which the radioactive material is diluted, the concentration levels reached in fish and shellfish, the factors regarding removal to sediments and exchange rates of water bodies, and the number of individuals who use the water for drinking purposes and who consume fish.

200. The local and regional collective dose commitments from radionuclides in liquid effluents can be estimated using the expression

$$S_i^c = \frac{A_i}{V(\tau + \lambda_i)} \sum_k N_k f_{k,i} I_k d_i \qquad (33)$$

where A_i (Bq) is the activity of radionuclide i released to water; V (liters) is the volume of the receiving water; τ (a^{-1}) is the reciprocal of the mean residence time of a radionuclide in the receiving water assuming no decay (removal to sediments is incorporated implicitly in this value); λ_i (a^{-1}) is the radioactive decay constant for radionuclide i; N_k is the number of individuals for pathway k; $f_{k,i}$ (Bq kg^{-1} per Bq l^{-1}) is the concentration factor for an item in pathway k for radionuclide i; I_k (kg a^{-1}) is the individual consumption rate of pathway item k; d_i (Sv Bq^{-1}) is the effective dose per unit activity ingested.

201. The quantity $A/V(\tau + \lambda)$ (Bq a l^{-1}) is the integral concentration in water for release of an activity A (Bq) or, alternatively, the equilibrium concentration in water, $C_{w,i}$ (Bq l^{-1}), for a constant continuing release rate (Bq a^{-1}). The equilibrium concentration in fish or shellfish is $C_{w,i}f_{k,i}$ (Bq kg^{-1}), where $f_{k,i}$ is the appropriate freshwater or salt-water concentration factor.

202. For radionuclide releases to small volumes of water, the concentrations in water or fish may be high, but the population that can be served with drinking water or by fish production will be limited. For releases to larger water volumes, the concentrations will be less, but the populations involved will be correspondingly larger. In fact, the N_k/V relationship could be taken, in a crude approximation, as relatively constant, the inverse of which indicates the water use with regard to the specific pathway, k, of each individual in the population.

203. For the drinking water pathway, a value for the quotient V/N_k of $2.2\ 10^7$ l man^{-1} is assumed for estimating the collective dose commitments from generalized liquid releases. This value is assumed to be a global average and

is obtained from an estimated global total of $1.3\ 10^{17}$ l of freshwater in lakes ($1\ 10^{17}$ l) and rivers (annual flow $0.3\ 10^{17}$ l) [U7], serving a world population of $6\ 10^{9}$.

204. Average fish plus seafood consumption per individual is about 8 kg a^{-1}, ranging from 4 to 6 kg a^{-1} in the Near East and Africa to 10–14 kg a^{-1} in the Far East and Europe [I7]. It may be assumed that the annual consumption is 6 kg a^{-1} ocean fish, 1 kg a^{-1} freshwater fish and 1 kg a^{-1} shellfish. Total freshwater fish consumption by the world population is thus $6\ 10^{9}$ kg a^{-1}, which, when a correction is made for an edible weight of 50%, agrees with the estimated annual global harvest of 10^{10} kg landed weight [F2]. Dividing by the global freshwater volume given in the above paragraph, the result is $4.6\ 10^{-8}$ man kg a^{-1} l^{-1}, which will be assumed to be the factor $N_k I_k/V$ needed for estimating collective doses from freshwater fish consumption.

205. The annual global ocean fish and shellfish harvest is 10^{11} kg landed weight [F2], which is consistent with the ocean fish and shellfish consumption by the world population, $42\ 10^{9}$ kg a^{-1}. The catch mostly takes place within the continental shelf over an area of $27.5\ 10^{6}$ km^2 and with a mean depth of approximately 50 m [K1]. The volume of these waters is thus $1.4\ 10^{18}$ l. The factor $N_k I_k/V$ required for the salt-water fish and shellfish pathway is, therefore, $3\ 10^{-8}$ man kg a^{-1} l^{-1}. This is about 35 times higher than the factor used in the UNSCEAR 1977 Report [U7]. The mean residence time of the water over the continental shelf is assumed to be the same as that observed for the North Sea, i.e. approximately 3 years for ^{90}Sr and ^{137}Cs [N2] and 3.5 years for $^{239,240}Pu$ (first pass). Experience from Chernobyl has shown the turnover time of ^{137}Cs in freshwater systems to be 0.3 a^{-1}, i.e. similar to the turnover observed in coastal waters. This turnover rate is less by a factor of 3 than the value of 1 a^{-1} used in the UNSCEAR 1977 Report [U7]. For ^{90}Sr, the turnover rate in freshwater systems is 0.2 a^{-1}, somewhat less than for ^{137}Cs, owing to a lower sedimentation rate.

206. The specific-activity concepts for tritium and ^{14}C discussed above apply in aqueous systems as well as in terrestrial systems. HTO released to a water body is transported in the same way as other radionuclides but with the additional process of evaporation, which can have a large influence on HTO concentrations in some systems [H5]; neglecting this evaporation will result in overestimates of the tritium concentration. For an atmospheric release, concentrations in water bodies are usually much less than in air because of the large amounts of water available for dilution. Uptake of HTO by aquatic organisms is very quick: concentrations in tissue become equal to water concentrations within minutes or hours. Aquatic plants form organically bound tritium through photosynthesis. Fish and invertebrates also produce small amounts of organically bound tritium from the HTO in their bodies and can directly incorporate organically bound tritium taken up through ingestion.

207. The calculations made here of local and regional collective doses from tritium and ^{14}C in liquid effluents are based on equation (33) rather than on the specific-activity model. Because tritium concentrations in water and aquatic organisms are essentially the same, $f_{k,i} = 1$ for tritium. On the other hand, $f_{k,i}$ for ^{14}C is very high, since the carbon content of the organisms is much greater than the carbon content of water.

208. The parameters used and the estimates of collective dose per unit release of radionuclides to the aquatic environment are given in Tables 27 and 28. The estimates are the local and regional components of collective dose. Many radionuclides have been included that might have to be considered in specific circumstances. For releases of all radionuclides other than tritium in liquid effluents from reactors, it is useful to specify a representative composition, as was done for particulates in airborne effluents. The release composition can vary widely depending on the reactor type, the fuel integrity and the waste management practices. A representative composition is given in Table 29, which is derived from previously reported data [U3, U4]. Although these referred mainly to PWRs and BWRs, the composition can be taken to be reasonably applicable to all reactor types. For analysis of worldwide releases from reactors, the Committee has used an average of the results for releases to freshwater and to salt water. In this case, the estimated collective dose per unit release of the representative composition of radionuclides in liquid effluents is 330 man Sv PBq^{-1}. More appropriate selections and weightings of values can be made in applications to actual circumstances of releases from specific sources.

209. For many radionuclides, sediment removal considerations and radioactive half-lives limit the contributions to global collective doses. Only a few radionuclides achieve widespread, global dispersion, and these are considered in the following Chapter.

V. GLOBALLY DISPERSED RADIONUCLIDES

A. TRITIUM

210. Estimates of doses from globally dispersed tritium are required for three sources: natural occurrence, atmospheric nuclear testing, and nuclear power production. The most direct estimates of dose are obtained from measurements of the environmental concentrations of tritium, which have been made at a number of locations worldwide and from which individual doses from natural tritium and tritium produced in atmospheric testing may be inferred. Collective doses can be determined from an assumed variation of dose with latitude and the known population distribution. Doses from globally dispersed tritium arising from nuclear power production cannot be derived in this way, since the concentrations are undetectable beyond a few kilometres from the release point. Instead, the doses are estimated from model calculations.

211. The Committee based its estimate of the annual effective dose from natural tritium on measurements of the uniform levels of tritium in surface waters (and in the human body) prior to input from man-made sources. The estimated effective dose to individuals is 10 nSv a^{-1} [U7]. With reference to the total annual production of natural tritium of 72 PBq a^{-1} (see Annex B, "*Exposures from natural radiation doses*") and the present world population of 6 10^9, the collective dose per unit release is 6 10^9 × 10 nSv a^{-1} ÷ 72 PBq a^{-1} = 0.8 man Sv PBq^{-1}. Considering the population of each hemisphere (89% north, 11% south), the collective doses per hemispheric input are 1.5 man Sv PBq^{-1} for the northern hemisphere and 0.2 man Sv PBq^{-1} for the southern hemisphere.

212. The doses from tritium produced in atmospheric testing were estimated initially from measurements of the concentrations in surface waters [B3]. The estimated dose commitments were 20 μSv in the northern hemisphere and 2 μSv in the southern hemisphere [U7]. Based on estimated inputs of tritium into the atmosphere from the practice of 1.9 10^{20} Bq to the northern hemisphere and 0.5 10^{20} Bq to the southern hemisphere [U6] and applying the natural tritium dose/production rate ratio, the estimates of dose commitment were adjusted to 51 μSv and 14 μSv in the northern and southern hemispheres, respectively [U6]. These last values were derived from and correspond to the dose coefficients given at the end of the previous paragraph.

213. The models used to estimate the global doses from tritium similate the world hydrological cycle. Calculations are thereby made of the specific activity of tritium in the various global water pools. Most tritium is released to the atmosphere as HTO, and tritium gas (HT, T_2) is transformed in the soil to HTO. Tritium, therefore, follows the local and global water cycles. The hydrological models are invariably formulated in terms of compartments, in which the tritium is assumed to be instantaneously and uniformly mixed. Transfers between compartments are quantified using rate constants that are based on the known rates of water movement due to processes such as precipitation, evapotranspiration and run-off. Tritium concentrations in foodstuffs are assumed to equal concentrations in air moisture, soil water or surface water, depending on the model. The concentration of tritium in humans is calculated from an average of the concentrations in the sources of water ingested, weighted by the relative amount that each source contributes to intake. Several models of this kind exist, differing primarily in the number and size of compartments considered. The compartment approach is sufficient to calculate mean tritium concentrations over long times and large spaces. As well as providing estimates of doses from nuclear power production, the models can be used to confirm the doses from natural production and atmospheric testing deduced from observations.

214. The simplest model for estimating global tritium doses consists of single compartments representing the circulating waters of the hemispheres (to an ocean depth of 75 m). The model of Kelly et al. [K3], as implemented by NRPB and the Commissariat à l'Energie Atomique (CEA) [N2], used this basic approach and allowed for slow exchanges between the hemispheres and the deep oceans. For a release to the atmosphere or to surface waters, the collective dose per unit release was determined to be 0.028 man Sv PBq^{-1} relevant to a world population of 4 10^9. The Committee used this result in the UNSCEAR 1982 Report [U6] and adjusted it in the UNSCEAR 1988 Report [U5] to 0.032 man Sv PBq^{-1} for a population of 4.6 10^9. These results are probably underestimates of doses, because the tritium is mixed in large compartments that include the world's oceans and is diluted more than it would be in the terrestrial environment normally accessible by humans.

215. Improved estimates of the global dose from tritium are obtained using more realistic models developed by the NCRP [N3], Bergman et al. [B4] and Killough and Kocher [K2]. The seven compartments in the NCRP model represent atmospheric water, surface soil water, surface streams and freshwater lakes, groundwater, saline lakes and inland seas, the ocean surface and the deep ocean (Figure V). Water volumes and mean residence times of water in each compartment were estimated, together with fractional transfer rates for movement among the compartments. The volumes and transfer rates for the hemispheres and the world are listed in Table 30. The intake of tritium by man was calculated from the predicted environmental concentrations and the amount of water taken in through drinking and food ingestion. Eighty percent of drinking water was assumed to come from surface streams and freshwater lakes and 20% from deep

groundwater. Tritium concentration in plant water was assumed equal to $0.7\ C_a + 0.3\ C_s$, where C_a and C_s are the concentrations in air moisture and soil water, respectively. Although the NCRP model is not divided into latitude bands, it can be used to estimate doses from releases to different parts of the atmosphere by adjusting the size of the compartments to hemispheric or latitudinal water volumes.

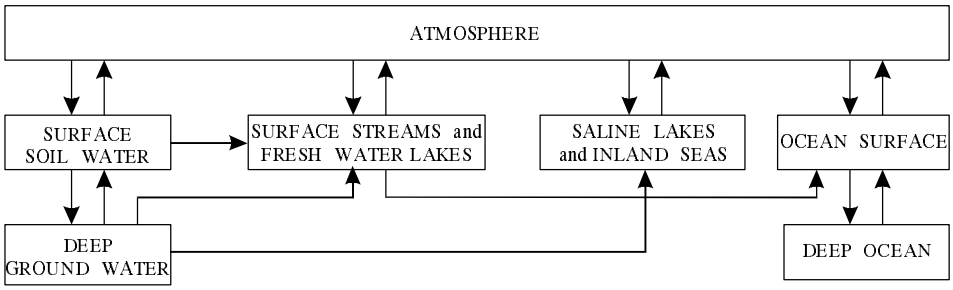

Figure V. Seven-compartment model of the hydrological cycle for global circulation of tritium [N3].

216. The model developed by Bergman et al. [B4] improved on the NCRP model by dividing all compartments into two latitude zones in each of the northern and southern hemispheres. It included a separate reservoir for organically bound tritium in terrestrial biota and was able to account for HT releases. The Killough and Kocher model [K2] separates the atmosphere into stratosphere and troposphere and further subdivided all atmosphere and ocean compartments, allowing the model to account for latitudinal inhomogeneities. Killough and Kocher noted that, without the stratospheric compartments, HTO entering the northern atmosphere is removed too rapidly to permit significant interhemispheric transport, and estimates of doses from atmospheric nuclear testing are unreliable. The use of a diffusive ocean module improved the ability of the model to estimate concentrations in the surface waters of the ocean.

217. The estimates of global collective doses from atmospheric tritium releases obtained with several models are shown in Table 31, together with the estimates based on natural tritium production. The estimates of the model calculations are those available in published reports, since with the exception of the NCRP model, the codes are too poorly documented to be run independently. The results are not easily compared since different source distributions are used. In general, however, there is a relatively good level of agreement. The dose estimates for releases to the global atmosphere are within a factor of 2, regardless of whether latitudinal zonation is considered or not. This level of agreement is maintained for releases to the northern hemisphere, but differences by a factor of 10 arise for releases to the southern hemisphere. The estimate of Bergman et al. [B4] for release to the global stratosphere (0.76 man Sv PBq^{-1}) agrees well with the global dose from natural production (0.8 man Sv PBq^{-1}). The NCRP results tend to be lower than those of the other models. Killough and Kocher [K4] found that the NCRP model underestimates observed freshwater concentrations of fallout tritium by about an order of magnitude and overestimates ocean concentrations by a factor of 3. Use of the NCRP model therefore likely leads to underestimates of the global collective doses from releases of tritium.

218. The global collective dose from near-surface atmospheric releases from nuclear installations is best obtained from model estimates of releases to the 30°–50° band of the troposphere in the northern hemisphere. The Killough and Kocher estimate of 2.3 man Sv PBq^{-1} is the most reliable in this regard. The NCRP model result is 0.7 man Sv PBq^{-1} for this case, but as noted above, this is probably an underestimate. The northern hemispheric estimate from natural production, 1.5 man Sv PBq^{-1}, may also reflect doses due to releases from nuclear installations, although it, too, may be an underestimate because the release is not confined to the latitude band in which the greatest population density is found.

219. Estimates of the global collective dose arising from releases to the ocean from nuclear installations are available from both the NCRP and Bergman et al. models. Both obtain estimates of doses that are about one tenth lower than those resulting from atmospheric releases. Taking the atmospheric result to be 2.3 man Sv PBq^{-1}, the dose from releases to the ocean becomes 0.2 man Sv PBq^{-1}.

220. Estimating the global distribution of tritium released from nuclear installations is a difficult task, and calculated doses contain an element of uncertainty. Based on a comparison of model estimates with observations [K2] and on the level of agreement among the estimates of the more reliable models, the true value of the global collective dose is believed to lie within a factor of 3 of the values given above. Much of the uncertainty is due to the large size of the compartments used in the models. The average concentrations assumed throughout these compartments are incompatible with the rapid changes in concentration that occur in the environment surrounding local sources and the non-uniform population density that actually exists.

221. The seven-compartment NCRP model may be used to demonstrate the spatial and temporal variations in the estimated tritium doses (Tables 32 and 33).These results should be considered illustrative only, since the NCRP model does not include latitudinal zonation and it tends to underestimate doses. However, it is well documented, transparent and accessible, and its estimates are probably realistic in terms of trends if not of magnitudes. Such results from use of other models are unavailable to the Committee.

222. Results of the seven-compartment model [N3] for releases to different parts of the atmospheric compartment are presented in Table 32. The slight difference between the northern and southern hemisphere reflects the fact that more of the global land surface (67%) is in the northern hemisphere and more of the global ocean surface (57%) is in the southern hemisphere.

223. The time course of the delivery of dose from tritium released to the atmosphere is indicated in Table 33. In this example, the seven-compartment model [N3] is applied to the 30°–50° latitude band of the northern hemisphere. The distribution of tritium within the seven compartments is indicated, with the decreasing total reflecting radioactive decay. The concentrations of tritium within the compartments may be determined by dividing by the water volumes: $1.7\ 10^{12}$ m^3 in the atmosphere, $1.4\ 10^{13}$ m^3 soil water, $5.6\ 10^{13}$ m^3 in freshwater, $9.9\ 10^{13}$ m^3 in saline water, $1.8\ 10^{15}$ m^3 in groundwater, $2.7\ 10^{15}$ m^3 in the ocean surface, and $1.3\ 10^{17}$ m^3 in the deep ocean. The concentration in humans is determined from the concentrations in the environment, weighted for fractional daily intake: 0.99 l from the atmosphere, 0.77 l from soil water (foods), 1.22 l from drinking water (80% from fresh water and 20% from groundwater) and 0.02 l from the ocean surface (seafood) for a total daily water intake of 3 l. The effective dose is largely received within the first few years of release, since much of the tritium is by then transferred to the oceans, from which less than 1% of the water intake by humans is derived.

224. From the above discussion it would appear that some consolidation of the results of tritium modelling would be useful in order to be somewhat more certain about the best estimates of global doses. On the whole, however, dose estimates can be selected that should be adequate for the general purposes. In summary, the estimates of the global collective doses per unit release of tritium from various sources are 0.8 man Sv PBq^{-1} for natural production, 1.5 and 0.2 man Sv PBq^{-1} for northern and southern hemisphere releases from atmospheric testing, and 2 and 0.2 man Sv PBq^{-1} for airborne and liquid discharges from nuclear installations.

B. CARBON-14

225. After its release, carbon is distributed among the various reservoirs of the global carbon cycle: the atmosphere, the terrestrial biosphere, the hydrosphere, and the lithosphere. The fluxes of radiocarbon and stable carbon between the different reservoirs are governed by the same exchange processes. Isotopic fractionation is negligibly small, within the other uncertainties involved. The total carbon content in the atmosphere is about $7.5\ 10^{17}$ g, of which the overwhelming bulk is present as CO_2. Exchange of carbon with the terrestrial biosphere and the hydrosphere is estimated to be $2\ 10^{17}$ g a^{-1}, with more than half going to the biosphere. The largest reservoir is the lithosphere ($7.2\ 10^{22}$ g), but the exchange rates between this and other compartments are extremely low.

226. Because of the long half-life of ^{14}C, its consequences must be evaluated through the collective effective dose commitment, which is complete about 50,000 years after the release. About 70% of the collective effective dose commitment will have been delivered by 10,000 years. Most models assume that the global population grows until the middle of the next century and then stabilizes at 10^{10} people.

227. As with tritium, the most direct estimates of global ^{14}C dose are obtained from environmental measurements. A natural production rate of 1 PBq a^{-1} leads to an individual effective dose rate of 12 μSv a^{-1}. This implies a collective effective dose commitment of 120,000 man Sv PBq^{-1} if it is assumed that the equilibrium population of the world of 10^{10} is achieved within a short time compared with the mean environmental lifetime of ^{14}C.

228. Recent interest in climate change has led to the development of many models to study the global circulation of stable carbon. For the most part, these models cannot be used to calculate global ^{14}C doses without major modifications. The models discussed below are those developed specifically to assess the doses from man-made sources of radiocarbon. As was the case for tritium, they are all compartment models of varying complexity. The assumption of instantaneous mixing in compartments is invalid in the short term for ^{14}C but is sufficiently accurate for long-term dose assessment. The models predict activities per gram carbon in each environmental compartment over time. Once mixing is achieved, the specific-activity model may be used to estimate collective dose commitments from ^{14}C. It is assumed that the specific activity of ^{14}C in the carbon ingested by humans is the same as that in the most relevant compartments for food intake (ground vegetation for terrestrial foods and relevant surface ocean compartments for marine foods).

229. The long time required to deliver the dose means that details of the source location and distribution are not as important for ^{14}C as they were for tritium. For all doses derived from model calculations, the release was assumed to be to a single compartment representing the global atmosphere, and the results apply equally to ^{14}C releases from natural production, atmospheric testing and nuclear power production.

230. The models for global carbon dose consider radiocarbon only in the form of $^{14}CO_2$, as this is the only form in which ^{14}C can enter the food chain. Thus, $^{14}CO_2$ is

the only direct contributor to ingestion dose, which makes up 99% of the total ^{14}C dose. Assuming that all radiocarbon is released as $^{14}CO_2$ will overestimate doses if hydrocarbons are also present in the emissions. However, the hydrocarbons will be oxidized to $^{14}CO_2$ within a few years [E6], and this can be taken into consideration.

231. The ability to make reasonable time-dependent estimates of regional and global ^{14}C fluxes and doses from arbitrary release locations over thousands of years requires a fairly sophisticated model. It should include the atmosphere, biosphere with multiple compartments, soil, oceans with multiple layers (a well-mixed upper layer, unstirred dense thermocline, and deep water), and, possibly, ocean sediments. Input fluxes should include both ^{14}C and ^{12}C, so that the specific activity of the radiocarbon can be calculated. Recent models incorporate the influx of ^{12}C from the burning of fossil fuels.

232. The Committee has used a variety of methods to estimate global ^{14}C doses for releases from nuclear installations. The estimates in the UNSCEAR 1977 Report [U7] were calculated using a model with compartments for terrestrial biosphere, atmosphere and short-term biosphere combined; surface ocean, thermocline layer in the ocean (a diffusive layer), and deep ocean. The parameters were adjusted to fit measurements of excess ^{14}C in the atmosphere and surface ocean from atmospheric testing. The incomplete (to 10^4 years) whole-body collective dose commitment was found to be 120,000 man Sv PBq^{-1} for a future world population of 10^{10} people. In the UNSCEAR 1982 and 1988 Reports [U4, U6], the NRPB/CEA [N2] model was used to estimate an incomplete collective effective dose commitment of 67,000 man Sv PBq^{-1} as an average for both atmospheric and aquatic releases for a population of 10^{10}, which was assumed constant during the integration period. A model developed by Emanuel et al. [E2] was used in the UNSCEAR 1993 Report [U3] that produced estimates of the incomplete collective dose commitment of 85,000 man Sv PBq^{-1} for a projected world population of 10^{10} people.

233. Global ^{14}C modelling has been further advanced by the work of Titley et al. [T1], and this model is recommended for use in ^{14}C dose assessments. It contains 23 compartments (Figure VI): atmosphere, ocean sediments, Antarctic Ocean (four layers), Atlantic Ocean (four layers), Pacific Ocean, including the Indian Ocean (three layers), Arctic Ocean (two layers), woody tree parts, non-woody tree parts, ground vegetation, decomposers, soil, and a compartment representing input from fossil fuel burning. The terrestrial portion of the model was adapted from Emanuel et al. [E1] with minor modifications to allow the transfer of soil via rivers to the ocean surface compartments. Exchanges between the atmosphere and the terrestrial biosphere are based on estimates of the photosynthetic uptake of carbon by plants and its release to the atmosphere by plants, animals, and soil by respiration [C4, E1].

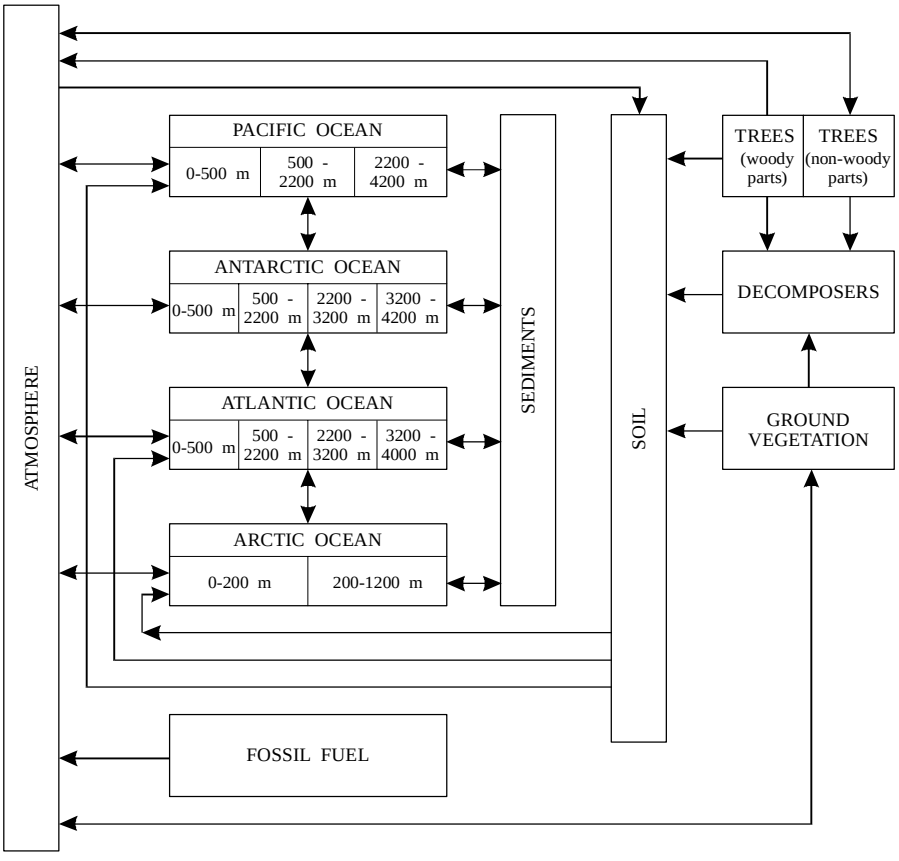

Figure VI. Compartment model for global circulation of carbon-14 [T1].

234. The ocean model in Titley et al. [T1] takes into account temperature changes, surface areas and varying amounts of ice cover in winter. Photosynthesis in the surface ocean layers and subsequent transfer of carbon down the water column was included and found to be important. In contrast, net sedimentation from water to the seabed was found to be a relatively insignificant process. The parameter values for the oceanic compartments were derived from several references [B6, M1, S3]. Exchanges between the oceanic and atmospheric compartments were based on estimates of the dissolution of CO_2 at the ocean/atmosphere interface using data from Mobbs et al. [M1] and Siegenthaler [S3]. Carbon dioxide is very soluble, and exchange with the atmosphere is rapid in open aerated water. The model was tested and validated against stable carbon distributions and ^{14}C specific activities arising from natural sources and atmospheric nuclear testing [T1].

235. The model of Titley et al. [T1] provides an estimate of the complete collective effective dose commitment per unit release: 109,000 man Sv PBq^{-1}. This is similar to the estimate of Emanuel et al. (108,000–114,000 man Sv PBq^{-1}), to the estimate derived from natural ^{14}C production (120,000 man Sv PBq^{-1}) and to previous UNSCEAR estimates. Indeed, the ^{14}C dose estimates of the many models in the literature are all very consistent. Killough and Rohwer [K5] found that the predictions of six models ranged over a factor of only 1.5. A similar range was found by Titley et al. [T1] in their comparison of four other models. Finally, McCartney et al. [M5] found less than a 15% difference in the results of three models. Killough and Rohwer [K5] attribute the consistency to the long half-life of ^{14}C relative to its rate of environmental transport, which makes the estimated dose commitments insensitive to the detailed structure of the models or to the values of the parameters used in them.

236. The collective dose coefficient of 109,000 man Sv PBq^{-1} was calculated with the assumption that the release is to the atmosphere, that the future world population stabilizes at 10^{10} people, and that the global inventory of stable carbon does not increase from its present value. Based on the values provided by the various models, there is a high probability that a range of 100,000–140,000 man Sv PBq^{-1} will encompass the actual collective dose under these conditions. Assuming fossil fuels continue to be burned at the present rate of $5\ 10^{15}$ g carbon per year until supplies are exhausted, the best estimate of the collective dose (from predictions of the Titley model) is 92,000 man Sv PBq^{-1}, with a range of 80,000–130,000 man Sv PBq^{-1}. Doses following a release to soils or surface oceans are about the same as those for an atmospheric release, but doses from release to deep oceans would be about 20% lower.

237. The time course of collective dose for a release of ^{14}C to the atmosphere or to the ocean surface is shown in Table 34. The equilibrium specific activities assuming fixed, stable carbon inventories match those of natural ^{14}C production, which is of the order of 1 PBq a^{-1}. Estimates of dose are given for a variable inventory of stable carbon caused by the burning of fossil fuels. About 9% of the complete dose commitment from a single release is delivered within 100 years, 23% within 1,000 years and 75% within 10,000 years.

C. IODINE-129

238. Because of its very long half-life ($1.57\ 10^7$ a), ^{129}I may become widely distributed in the global environment much like stable iodine, ^{127}I, over a long time. Whether released into the atmosphere or into the aquatic environment, ^{129}I will eventually reach the oceans in a time period presumably shorter than its half-life. Iodine is released from the ocean into the atmosphere as organic iodine (mostly as methyl iodide) [L1] as a consequence of microbial activity. The emitted organic iodine is decomposed by sunlight into inorganic iodine compounds. Both the organic and inorganic forms enter the terrestrial environment by the processes of wet and dry deposition [W1]. The deposition velocity of inorganic iodine onto vegetation is about two orders of magnitude higher than that of organic forms [N4]. The global iodine cycle and the dynamic behaviour of iodine in the environment is being further studied to improve the estimates of doses from ^{129}I releases.

239. Doses to humans from ^{129}I are delivered principally by its incorporation into the body by ingestion or inhalation. Iodine accumulates primarily in the thyroid, but the low specific activity of ^{129}I (6.55 MBq g^{-1}) limits the activity of the radionuclide that can be present in the gland [T1]. Artificially produced ^{129}I is released into the environment from nuclear installations, and small amounts were also released in atmospheric nuclear testing.

240. The behaviour of iodine in the terrestrial environment is influenced by many factors, e.g. soil type, microbial activity, and chemical form. It is known that stable iodine accumulates in soil; iodine concentrations in soil are 10–1,000 times higher than those of the parent rocks. The levels of ^{129}I in soils collected from the vicinity of nuclear reprocessing plants are markedly higher than the levels in other places [B5, M7, R6]. Vertical distribution of ^{129}I in soil showed that most of the radionuclide is retained in the surface layer (<10 cm). These observations indicate that the transfer of ^{129}I from the terrestrial environment to the ocean would occur only relatively slowly.

241. A model of the global iodine cycle was developed by Kocher [K8]. The environmental compartments assumed in the model are the atmosphere, hydrosphere, lithosphere, and terrestrial biosphere. It is estimated that the mean residence time of iodine in surface soil is of the order of 10,000 years and that the mixing of iodine throughout the ocean would require 1,000 years or more. Therefore, the

most important parameter for determining dose rates and cumulative doses following the release of ^{129}I is the 10,000-year mean residence time of iodine in the surface soil region. It thus appears that for a realistic long-term population dose assessment, a progression from local to regional to global-scale models would be required [K8]. When the released ^{129}I reaches equilibrium with stable iodine, the specific-activity method could be used in the assessment.

242. In the specific-activity approach, the activity concentration of ^{129}I per unit mass of ^{127}I is assumed to be the same in sea water and in the human thyroid. Assuming that the concentration of stable iodine per unit mass of thyroid is 80, 180, 300, and 600 μg g^{-1} at ages 6 months, 4 years, and 14 years and for adults, respectively, and using the age distribution given previously, a specific activity of 1 Bq per gram of stable iodine in the thyroid would lead to an age-weighted annual thyroid dose of 1.5 10^{-7} Gy. Since the sea contains 3.8 10^{16} g stable iodine (water mass of 6 10^{23} g and iodine concentration in water of 0.064 μg g^{-1}), a release of 1 PBq ^{129}I results in a long-term specific activity of 0.026 Bq g^{-1}. The collective thyroid dose commitment arising from the discharges of ^{129}I would be about 9 10^{8} man Gy PBq^{-1}, assuming a world population of 10^{10} and no sink for iodine in the environment.

243. The compartment model for the global circulation of iodine is shown in Figure VII. This represents a revision [T1] of the model described by Kocher [K8] and modified by Smith and White [S4]. The inventories of stable iodine in the model compartments and the fluxes between them were determined from environmental measurements and from the requirement for mass balance. Iodine-129 released into any compartment is assumed to be transported with stable iodine, and so the specific activity of ^{129}I can be determined for each compartment. Intake of ^{129}I occurs by inhalation and by the ingestion of water and terrestrial and marine foods.

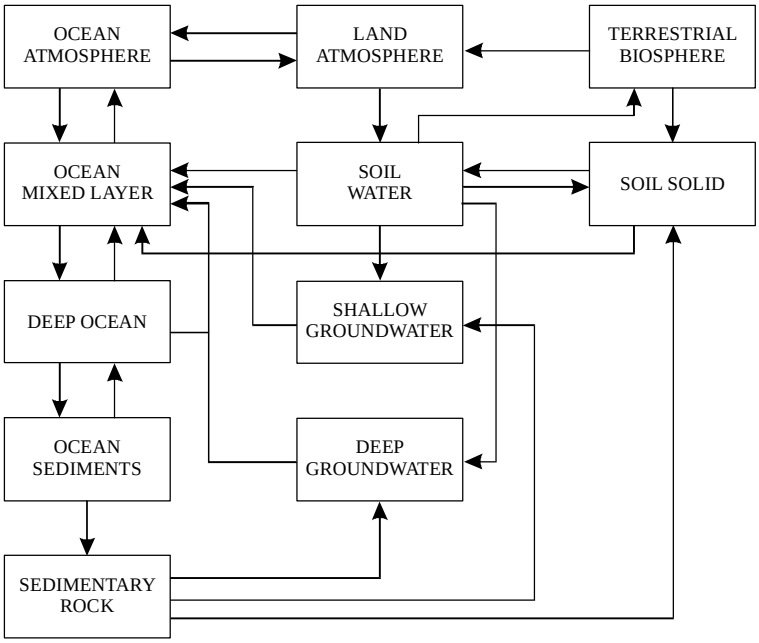

Figure VII. Compartment model for global circulation of iodine-129 [T1].

244. Important fluxes added to the global iodine model are from the sedimentary rock compartment to the two subsurface groundwater compartments and to the solid soil compartment, and from the solid soil compartment to the ocean mixed layer. This model includes the transfer of iodine from soil to the oceans and its subsequent movement back to soil from sedimentary rock. Titley et al. [T1] estimated the residence time of iodine in deep ocean waters to be 350 years and the flux of iodine from the deep ocean to the ocean mixed layer to be 2.3 10^{14} g a^{-1}. The amount of iodine transferred annually from the sedimentary rock compartment back to the solid soil compartment is estimated to be 1.8 10^{11} g a^{-1} [T1]. The mean residence times of iodine in the major compartments used in the model are 0.1 years in the ocean atmosphere, 0.09 years in the land atmosphere, 5.9 years in the ocean mixed layer, 19 years in the terrestrial biosphere, 3.6 10^{5} years in ocean sediments, 970 years in shallow subsurface region, and 38,000 years in deep subsurface region [T1].

245. The doses to individuals and collective doses following a release of ^{129}I can be calculated using the estimated time-dependent concentrations in the various compartments and either a pathway or a specific-activity analysis [K9]. The pathway analysis procedure involves identification of a number of exposure pathways; transfer coefficients are then used to estimate the movement of the radionuclide from the various compartments to humans. This approach requires considerable judgement because of the possible variations in the transfer coefficients and in the assumed intake rates, but the results are then quite realistic. The specific-activity approach is a means of

bypassing all the uncertainties and difficulties associated with the pathway analysis.

246. The pathway analysis method was adopted in the ^{129}I model under consideration. Five exposure pathways were assumed as follows: inhalation by humans from the land atmosphere, the daily intake rate of iodine being 0.29 μg d^{-1}; deposition from the land atmosphere onto food crops ingested directly by humans or by dairy and beef cattle and subsequently ingested by humans (6.6 μg d^{-1}); ingestion of land surface water directly by humans or by cattle (5.3 μg d^{-1}); ingestion of marine fish and shellfish from the ocean mixed layer (11 μg d^{-1}); root uptake from the surface soil region or from the soil water region into crops consumed by humans or by cattle subsequently ingested by humans. The intake of iodine through root uptake considers the concentration of iodine in the terrestrial biosphere and the ingestion of vegetables, cereals, all other foods, meat and milk. The daily intake of iodine through root uptake of iodine using average world consumption rates is 200 μg d^{-1}, and the total daily uptake of iodine is 220 μg d^{-1} [T1]. The calculation of effective dose utilized the following values: equivalent dose in the thyroid per unit intake 1.3 μSv Bq^{-1} (inhalation) and 2.1 μSv Bq^{-1} (ingestion) and tissue weighting factor 0.05.

247. A comparison of collective effective dose to the world population arising from a release of 1 TBq of ^{129}I during one year to the five different compartments calculated using this model [T1] is given in Table 35. At 10^8 years the collective effective dose for release to the land atmosphere (727 man Sv) and to solid soil (828 man Sv) are higher than the collective effective dose for release to the ocean compartments, 530, 469, and 469 man Sv for release to the ocean atmosphere, the ocean mixed layer and the deep ocean, respectively. The trend in collective effective doses from 50 years indicates higher amounts of iodine in the land atmosphere with negligible amounts in the deep ocean, but by 10^8 years the amounts in the deep ocean will have increased, while the amounts in the land atmosphere will have decreased. Thus the transfer to the deep ocean is much faster than the reverse process.

248. The long residence times of iodine in the solid soil compartment and the deep ocean compartment and the fact that a larger fraction of iodine in the ocean mixed layer compartments is transported downwards rather than to the atmosphere imply that it takes much longer for ^{129}I to reach the soil water compartment, from which most of the iodine intake by humans is derived. Collective effective doses estimated assuming that ^{129}I is discharged into the land atmosphere compartment are generally higher because of the direct connection between this compartment and the soil water compartment. The long residence time in the sedimentary rock compartment implies that iodine entering the sedimentary rock compartment is trapped there for a time of the same order as the half-life of ^{129}I before being cycled back to the soil.

CONCLUSIONS

249. In this Annex, the procedures used by the Committee for calculating doses from radionuclides in the environment are reviewed and updated. The radionuclides considered are those present either because they occur naturally or they have been released by anthropogenic practices. Although the calculational procedures are well established from extensive measurement and modelling experience, the increasing knowledge of transfer processes and radionuclide behaviour and better judgement of representative conditions allow the relevant parameters to be adjusted and the dose estimates to be improved.

250. For the Committee's purposes of estimating average doses under general conditions of release or presence of radionuclides in the environment, relatively simple calculational methods are sufficient. More detailed, time-dependent or otherwise complex methods have not been considered. For releases to the atmosphere or to the aquatic environment, such as those that occur from nuclear installations, average annual doses per unit release are estimated for populations in the local and regional areas. For longer-lived radionuclides that become widely dispersed, the average global doses are also evaluated. The main pathways of external irradiation, inhalation, and ingestion are considered.

251. The Committee has selected representative parameters to reflect the various conditions of release, environmental transport and behaviour, and the personal habits of intake and metabolism of the various radionuclides. These should provide reasonably accurate estimates of dose in many applications. Alternative selections of the parameters may lead to wide variations in the dose estimates. Therefore, the methods presented in this Annex should be used with caution. In particular, it is recommended that site-specific data should be used as appropriate and when available.

Table 1
Radiation weighting factors
[I1]

Type of radiation	*Energy range*	*Radiation weighting factor w_R*
Photons, electrons, muons	All energies	1
Neutrons Protons	<10 keV, >20 MeV >2 MeV	5 5
Neutrons	10-100 keV, >2-20 MeV	10
Neutrons Alpha particles, fission fragments, heavy nuclei	>0.1-2 MeV All energies	20 20

Table 2
Tissue weighting factors
[I1, I11]

Tissue or organ	*Weighting factor w_T*	
	1977	*1990*
Gonads	0.25	0.20
Breast	0.15	0.05
Colon		0.12
Red bone marrow	0.12	0.12
Lungs	0.12	0.12
Stomach		0.12
Urinary bladder		0.05
Liver		0.05
Oesophagus		0.05
Thyroid	0.03	0.05
Bone surface	0.03	0.01
Skin		0.01
Remainder	0.30 [a]	0.05 [b c]

a The value 0.06 is applied to the average dose among each of the five remaining organs or tissues receiving the highest dose, excluding the skin, lens of the eye, and the extremities.

b The remainder is composed of the following tissues and organs: adrenals, brain, extrathoracic region of the respiratory tract, small intestine, kidney, muscle, pancreas, spleen, thymus, and uterus.

c The value 0.05 is applied to the average dose to the remainder tissue group. However, when the most exposed remainder tissue or organ receives the highest committed equivalent dose of all organs, a weighting factor of 0.025 is applied to that organ and a weighting factor of 0.025 is applied to the average dose in the rest of the remainder.

Table 3
Values of the parameters used to evaluate vertical dispersion in the Gaussian plume model

Stability class	*Stability-dependent parameters*			
	a	*b*	*c*	*d*
A: extremely unstable	0.112	1.060	$5.38\ 10^{-4}$	0.815
B: moderately unstable	0.130	0.950	$6.52\ 10^{-4}$	0.750
C: slightly unstable	0.112	0.920	$9.05\ 10^{-4}$	0.718
D: neutral	0.098	0.889	$1.35\ 10^{-3}$	0.688
E: slightly stable	0.0609	0.895	$1.96\ 10^{-3}$	0.684
F: moderately stable	0.0638	0.783	$1.36\ 10^{-3}$	0.672
Roughness length (m)	*Roughness-dependent parameters*			
	p	*q*	*r*	*s*
0.01: Lawns, water bodies	1.56	0.048	$6.25\ 10^{-4}$	0.45
0.04: Plowed land	2.02	0.0269	$7.76\ 10^{-4}$	0.37
0.1: Open grassland	2.72	0	0	0
0.4: Rural areas, small villages	5.16	-0.098	18.6	-0.225
1.0: Forest, cities	7.37	-0.0957	$4.29\ 10^{3}$	-0.60
4.0: Cities with tall buildings	11.7	-0.128	$4.59\ 10^{4}$	-0.78

Table 4
Representative values of meteorological and release parameters

Parameter	*Units*	*Value*					
Effective release height (H)	m	30					
Direction frequency (f_i)	Dimensionless	0.083					
Sector width ($\Delta\theta$)	Radians	0.524					
Roughness length (z_0)	m	0.4					
		Stability class					
		A	*B*	*C*	*D*	*E*	*F*
Frequency of occurrence (f_i)	Dimensionless	0.05	0.10	0.20	0.30	0.20	0.15
Wind speed (u_i)	m s^{-1}	2	3	4	5	3	2
Inversion height (h_i)	m	2 000	1 500	1 200	800	400	200

Table 5
Dilution factors for the representative source and long-term average conditions

Downwind distance (km)	*Dilution factor (Bq m^{-3} per Bq s^{-1})*
0.5	$9.7\ 10^{-7}$
1	$5.3\ 10^{-7}$
2	$2.5\ 10^{-7}$
5	$7.1\ 10^{-8}$
10	$2.5\ 10^{-8}$
20	$8.7\ 10^{-9}$
50	$2.2\ 10^{-9}$
100	$7.6\ 10^{-10}$
200	$2.7\ 10^{-10}$
500	$6.7\ 10^{-11}$
1 000	$2.4\ 10^{-11}$
2 000	$8.2\ 10^{-12}$

Table 6
Analysis of variability in results of the Gaussian plume model

Varied parameter	*Value of varied parameter*	*Dilution factor at 1 km*	*Exponent of power function*
Wind speed (u_i)	Twice the representative value	$2.6\ 10^{-7}$	1.39
	Half the representative value	$1.1\ 10^{-6}$	1.55
Mixed layer height (h_i)	Twice the representative value	$5.3\ 10^{-7}$	1.55
	Half the representative value	$5.3\ 10^{-7}$	1.37
Frequency of stability class (f_i)	0.02, 0.05, 0.15, 0.55, 0.15,0.08 for classes A, B, C, D, E, F (high proportion of neutral classes)	$5.0\ 10^{-7}$	1.44
	0.02, 0.05, 0.15, 0.25, 0.3, 0.23 for classes A, B, C, D, E, F (high proportion of stable classes)	$5.8\ 10^{-7}$	1.49
	0.15, 0.25, 0.3, 0.2, 0.05, 0.05 for classes A, B, C, D, E, F (High proportion of unstable classes)	$4.4\ 10^{-7}$	1.41
Surface roughness (z_0)	0.1 m	$5.1\ 10^{-7}$	1.46
	1.0 m	$5.3\ 10^{-7}$	1.44
Effective release height (H)	0 m (ground-level release)	$1.2\ 10^{-6}$	1.70
	60 m	$2.2\ 10^{-7}$	1.36
Dry deposition velocity (v_d)	0.01 m s^{-1}	$5.2\ 10^{-7}$	1.74
	$4\ 10^{-4}$ m s^{-1}	$5.3\ 10^{-7}$	1.31
	0 m s^{-1}	$5.3\ 10^{-7}$	1.21
Wash-out coefficient (Λ)	$3\ 10^{-4}$ s^{-1}	$5.3\ 10^{-7}$	1.46
	$3\ 10^{-5}$ s^{-1}	$5.3\ 10^{-7}$	1.46
v_d and Λ	0	$5.3\ 10^{-7}$	1.21

Table 7
Outdoor effective dose rate to the adult per unit concentration in soil for the significant naturally occurring radionuclides

Radionuclide	*Effective dose rate per unit concentration (nSv h^{-1} per Bq kg^{-1})*		
	[B8] [a]	*[S10, S11]* [b]	*[E7]* [b]
^{40}K	0.029	0.030	0.033
^{232}Th series	0.46	0.42	0.51
^{238}U series	0.30	0.31	0.35

a Calculated as $E = X \times 0.0087$ Gy $R^{-1} \times 0.7$ Sv Gy^{-1}.
b $H_E + 0.01\ H_{skin}$.

Table 8
Conversion coefficients from air kerma to effective dose for terrestrial gamma rays
[S11]

Radionuclide	*Effective dose per unit air kerma (Sv Gy^{-1})*		
	Infants	*Children*	*Adults*
^{40}K	0.926	0.803	0.709
^{232}Th	0.907	0.798	0.695
^{238}U	0.899	0.766	0.672
Average	0.91	0.79	0.69

Table 9
Effective dose factors for cloud immersion

Radionuclide	*Effective dose per unit time-integrated concentration in air (nSv per Bq d m^{-3})*	
	[K7] [a]	*[E7]* [a]
^{89}Sr	0.033	0.039
^{90}Sr [b]	0.062	0.079
^{95}Zr	2.9	3.1
^{95}Nb	3.0	3.3
^{99}Mo [b]	1.1	1.1
^{103}Ru [b]	1.8	2.0
^{106}Ru [b]	0.87	0.99
^{110m}Ag [b]	11	12
^{115}Cd [b]	1.4	1.6
^{125}Sb [b]	1.6	1.8
^{127}Sb [b]	2.6	3.0
^{129m}Te [b]	0.29	0.32
^{131m}Te [b]	6.0	6.5
^{131}I	1.4	1.6
^{132}Te [b]	9.8	11
^{133}I	2.3	2.6
^{134}Cs	6.0	6.6
^{136}Cs	8.5	9.3
^{137}Cs [b]	2.2	2.4
^{140}Ba	0.72	0.76
^{140}La	9.3	10
^{141}Ce	0.29	0.31
^{143}Ce	1.0	1.1
^{144}Ce [b]	0.27	0.31
^{239}Np	0.64	0.68

a Calculated as $H_E + 0.01\ H_{skin}$.
b Decay products included.

Table 10
Collective effective doses from immersion exposure to noble gases released from reactors

Radionuclide	*Half-life*	*Effective dose rate per unit concentration* [a] *[E7] (nSv per Bq a m^{-3})*	*Collective dose per unit release* [b] *(man Sv PBq^{-1})*		
			Local	*Regional*	*Total*
^{41}Ar	1.827 h	2 080	0.90	0.005	0.90
^{85m}Kr	4.48 h	243	0.15	0.004	0.15
^{85}Kr	10.72 a	7.92	0.007	0.007	0.014
^{87}Kr	76.3 m	1 340	0.47	0.001	0.47
^{88}Kr	2.84 h	3 260	1.73	0.021	1.75
^{131m}Xe	11.9 d	13.8	0.012	0.009	0.021
^{133m}Xe	2.188 d	46.5	0.039	0.013	0.052
^{133}Xe	5.245 d	50.8	0.043	0.025	0.068
^{135m}Xe	15.29 m	653	0.062	- [c]	0.062
^{135}Xe	9.09 h	385	0.28	0.016	0.30
^{138}Xe	14.17 m	1 850	0.16	- [c]	0.16

a Evaluated as $H_E + 0.01\ H_{skin}$.
b Release from model reactor site; population density 400 km $^{-2}$ in local area (1-50 km) and 20 km $^{-2}$ in the regional area (50-2,000 km).
c Negligible result.

Table 11
Collective effective dose from immersion exposure for representative composition of noble gases released from reactors

Radio-nuclide	*Fractional release [U4]*		*Weighted collective dose per unit release [a] (man Sv PBq^{-1})*					
			PWRs			*BWRs*		
	PWRs	*BWRs*	*Local*	*Regional*	*Total*	*Local*	*Regional*	*Total*
^{41}Ar	0.005	0.03	0.005	0.00002	0.005	0.026	0.0001	0.027
^{85m}Kr	0.004	0.06	0.001	0.00002	0.0006	0.009	0.0002	0.010
^{85}Kr	0.016	0.01	0.0001	0.0001	0.0002	0.00009	0.00009	0.0002
^{87}Kr	0.009	0.08	0.004	0.00001	0.004	0.039	0.0001	0.039
^{88}Kr	0.004	0.15	0.007	0.00008	0.007	0.25	0.003	0.26
^{131m}Xe	0.006	0.03	0.00008	0.00006	0.0001	0.0004	0.0003	0.0007
^{133m}Xe	0.006	0	0.0002	0.00008	0.0003	0	0	0
^{133}Xe	0.81	0.20	0.035	0.020	0.055	0.009	0.005	0.014
^{135m}Xe	0.002	0.06	0.0001	-	0.0001	0.004	-	0.004
^{135}Xe	0.14	0.17	0.039	0.002	0.041	0.049	0.003	0.052
^{138}Xe	0.003	0.20	0.0005	-	0.0005	0.032	-	0.032
Total	1.0	1.0	0.09	0.02	0.11	0.42	0.01	0.43

a Collective dose per unit release (values from Table 10) multiplied by the release fraction. The results apply for the model reactor site.

Table 12
Transfer coefficients P_{25} from deposition to external exposure from radionuclides produced in atmospheric nuclear testing

Radionuclide	*Half-life*	*Absorbed dose rate in air per unit deposition density [a] (nGy a^{-1} per Bq m^{-2})*	*Effective dose commitment per unit deposition density [b] (nSv per Bq m^{-2})*
^{54}Mn	312.3 d	12.9	4.02
^{95}Zr [c]	64.02 d	45.0	2.87
^{103}Ru	39.26 d	10.8	0.42
^{106}Ru	373.6 d	3.21	1.19
^{125}Sb	2.76 a	6.52	6.54
^{131}I	8.02 d	13.0	0.10
^{137}Cs	30.07 a	8.89	97.2
^{140}Ba [c]	12.75 d	73.5	0.93
^{141}Ce	32.5 d	1.49	0.048
^{144}Ce [c]	284.9 d	0.693	0.20

a Ref. [B9]; converted with 0.869 rad per R and 0.01 Gy per rad. Assumes relaxation lengths of 0.1, 1, and 3 cm for radionuclides of half-lives <30 d, 30-100 d, and >100 d, respectively.

b Derived from absorbed dose rate in air times 0.7 Sv Gy^{-1} times 0.36 (occupancy/shielding factor) times mean-life (in years) of radionuclide (1.44 × half-life).

c Includes decay product.

Table 13
Annual components of dose from external exposure to radionuclides following a single deposition event

Year following deposition	*Annual effective dose per unit deposition density (nSv per Bq m^{-2})*									
	^{131}I	*^{140}Ba*	*^{141}Ce*	*^{103}Ru*	*^{95}Zr*	*^{144}Ce*	*^{54}Mn*	*^{106}Ru*	*^{125}Sb*	*^{137}Cs*
1	0.10	0.93	0.048	0. 42	2.82	0.12	2.23	0.59	1.45	2.21
2				0.001	0.054	0.05	0.99	0.30	1.13	2.16
3					0.001	0.020	0.44	0.15	0.88	2.11
4						0.008	0.20	0.08	0.68	2.07
5						0.003	0.09	0.039	0.53	2.02
6						0.001	0.039	0.020	0.41	1.97
7						0.0006	0.017	0.010	0.32	1.93
8						0.0002	0.008	0.005	0.25	1.88
9						0.0001	0.003	0.003	0.19	1.84
10							0.002	0.001	0.15	1.80
Total										
1-10	0.10	0.93	0.048	0.42	2.87	0.20	4.02	1.19	6.01	20.0
11-20							0.001	0.001	0.49	15.9
21-50									0.04	30.6
51-100										21.0
101-∞										9.69
Commitment										
1-∞	0.10	0.93	0.048	0.42	2.87	0.20	4.02	1.19	6.54	97.2

Table 14
Effective dose equivalent factors for external irradiation outdoors from deposited radionuclides
[B9, U4]

Radionuclide	*Effective dose equivalent per unit deposition density (nSv per Bq m^{-2})*	
	30 days to 1 year [a]	*After 1 year [b]*
^{103}Ru	0.691	0.00128
^{106}Ru	2.09	1.65
^{131}I	0.015	0.0
^{134}Cs	18.6	36.2
^{137}Cs	8.04	264

a Assumes relaxation length in soil of 1 cm.
b Assumes relaxation length in soil of 3 cm.

Table 15
Estimates of collective dose from external exposure per unit release of radionuclides from nuclear installations

Radionuclide	*Transfer coefficient P_{25} (nSv per Bq m^{-2})*	*Collective effective dose per unit release [a] (man Sv PBq^{-1})*		
		Local	*Regional*	*Total*
^{51}Cr	0.021	0.6	0.3	0.9
^{54}Mn	4.0	120	54	170
^{59}Fe	1.1	33	15	48
^{58}Co	1.1	32	14	46
^{60}Co	71	2 100	940	3 040
^{65}Zn	2.1	63	28	92
^{95}Zr [b]	2.9	85	38	120
^{103}Ru	0.42	13	5.7	18
^{106}Ru	1.2	35	16	51
^{124}Sb	2.3	69	31	100
^{131}I	0.10	3.1	1.4	4.5
^{134}Cs	18	540	240	780
^{136}Cs	0.92	27	12	40
^{137}Cs	97	2 890	1 300	4 190
^{140}Ba [b]	0.93	28	12	40
^{141}Ce	0.048	1.4	0.65	2.1
^{144}Ce [b]	0.20	5.8	2.6	8.5
^{241}Am	44	1 310	590	1 890
Particulates [c]		740	340	1 080

a Estimated from dispersion relationship: $5\ 10^{-7}\ x^{-1.4}$, where x is the distance from the release point; deposition velocity = 0.002 m s^{-1}; and population density = 400 km^{-2} in local area (1-50 km) and 20 km^{-2} in the regional area (50-2,000 km). Reduction due to urban runoff (factor of 0.75) also assumed.
b Includes decay product.
c Weighted average for assumed representative composition: 13% each of ^{54}Mn, ^{58}Co, ^{60}Co, ^{89}Sr, ^{134}Cs, ^{137}Cs, and ^{140}Ba; 0.9% each of ^{51}Cr, ^{59}Fe, ^{65}Zn, ^{90}Sr, ^{90}Y, ^{95}Zr, ^{124}Sb, ^{136}Cs, ^{141}Ce, and ^{144}Ce.

Table 16
Age-weighted breathing rate for the world population

Age group	*Breathing rate [a] (m^3 d^{-1})*	*Fraction of population [b]*	*Weighted rate (m^3 a^{-1})*
0-12 months	2.86	0.02	21
1-2 years	5.16	0.04	75
3-7 years	8.72	0.10	320
8-12 years	15.3	0.10	560
13-17 years	20.1	0.09	660
Adults (>17 years)	22.2	0.65	5 300
Sum		1.0	6 900

a Ref. [I4].
b Estimated from [U15].

Table 17
Committed effective doses per unit intake by inhalation of radionuclides
[I4, I5]

Radio-nuclide	*Absorption type* [a]	*Effective dose per unit intake (nSv Bq^{-1})*			*Radio-nuclide*	*Absorption type* [a]	*Effective dose per unit intake (nSv Bq^{-1})*		
		Infants [b]	*Children* [c]	*Adults* [d]			*Infants* [b]	*Children* [c]	*Adults* [d]
^{54}Mn	M	6.2	2.4	1.5	^{238}U series:				
^{55}Fe	M	1.4	0.62	0.38	^{238}U	M	9 400	4 000	2 900
^{89}Sr	M	24	9.1	6.1	^{234}U	M	11 000	4 800	3 500
^{90}Sr	M	110	51	36	^{230}Th	S	35 000	16 000	14 000
^{91}Y	M	30	11	7.1	^{226}Ra	M	11 000	4 900	3 500
^{95}Zr	M	16	6.8	4.8	^{210}Pb	M	3 700	1 500	1 100
^{95}Nb	M	5.2	2.2	1.5	^{210}Po	M	11 000	4 600	3 300
^{99}Mo	M	4.4	1.5	0.89					
^{103}Ru	M	8.4	3.5	2.4	^{232}Th series:				
^{106}Ru	M	110	41	28	^{232}Th	S	50 000	26 000	25 000
^{110m}Ag	M	28	12	7.6	^{228}Ra	M	10 000	4 600	2 600
^{115}Cd	M	4.8	1.7	0.98	^{228}Th	S	130 000	55 000	40 000
^{125}Sb	M	16	6.8	4.8					
^{127}Sb	M	7.3	2.7	1.7	^{235}U series:				
^{129m}Te	M	26	9.8	6.6	^{235}U	M	10 000	4 300	3 100
^{131m}Te	M	5.8	1.9	0.94	^{231}Pa	S	69 000	39 000	34 000
^{132}Te	M	13	4.0	2.0	^{227}Ac	M	550 000	260 000	220 000
^{131}I	F	72	19	7.4					
^{133}I	F	18	3.8	1.5	^{239}Np	M	4.2	1.4	0.93
^{134}Cs	F	7.3	5.3	6.6	^{238}Pu	M	74 000	44 000	46 000
^{136}Cs	F	5.2	2.0	1.2	^{239}Pu	M	77 000	48 000	50 000
^{137}Cs	F	5.4	3.7	4.6	^{240}Pu	M	77 000	48 000	50 000
^{140}Ba	M	20	7.6	5.1	^{241}Pu	M	970	830	900
^{140}La	M	6.3	2.0	1.1	^{241}Am	M	69 000	40 000	42 000
^{141}Ce	M	11	4.6	3.2					
^{143}Ce	M	3.9	1.3	0.75					
^{144}Ce	M	160	55	36					

a Absorption rates in body fluids are fast (F), moderate (M), and slow (S).
b From 1 year to 2 years.
c More than 7 years to 12 years.
d More than 17 years.

Table 18
Transfer coefficients for the inhalation pathway applicable to the deposition of radionuclides produced in atmospheric nuclear testing

Radionuclide	*Effective dose per unit intake* [a] P_{45} *(nSv Bq^{-1})*	*Effective dose per unit deposition density* [b] P_{245} *(nSv per Bq m^{-2})*
^{54}Mn	1.5	0.020
^{55}Fe	0.38	0.0050
^{89}Sr	6.1	0.080
^{90}Sr	36	0.47
^{91}Y	7.1	0.093
^{95}Zr	4.8	0.063
^{95}Nb	1.5	0.020
^{103}Ru	2.4	0.032
^{106}Ru	28	0.37
^{125}Sb	4.8	0.063
^{131}I	7.4	0.097
^{137}Cs	4.6	0.061
^{140}Ba	5.1	0.067
^{141}Ce	3.2	0.042
^{144}Ce	36	0.47
^{238}Pu	46 000	610
^{239}Pu	50 000	660
^{240}Pu	50 000	660
^{241}Pu	900	12
^{241}Am	42 000	550

a Absorption assumed to be Type F (fast) for ^{131}I and ^{137}Cs and Type M (moderate) for all other radionuclides.

b Equal to $P_{14}P_{45}/P_{12}$, where $P_{14} = 20$ m^3 d^{-1} (adult breathing rate) and $P_{12} = 0.0176$ m s^{-1} (the deposition velocity applicable to fallout from atmospheric testing).

Table 19
Estimates of collective dose from inhalation exposure per unit release of radionuclides from nuclear installations

Radionuclide	*Transfer coefficient P_{245} (nSv per Bq m^{-2})*	*Collective effective dose per unit release [a] (man Sv PBq^{-1})*		
		Local	*Regional*	*Total*
^{51}Cr	0.0037	0.15	0.07	0.21
^{54}Mn	0.17	6.9	3.1	10
^{55}Fe	0.044	1.7	0.8	2.5
^{59}Fe	0.43	17	7.6	25
^{58}Co	0.19	7.3	3.3	11
^{60}Co	1.2	46	21	66
^{65}Zn	0.19	7.3	3.3	11
^{89}Sr	0.71	28	13	41
^{90}Sr	4.2	165	74	240
^{90}Y	0.16	6.4	2.9	9.3
^{91}Y	0.82	33	15	47
^{95}Zr	0.56	22	9.9	32
^{103}Ru	0.28	11	5.0	16
^{106}Ru	3.2	130	58	190
^{124}Sb	0.74	29	13	43
^{131}I	0.86	34	15	49
^{134}Cs	0.76	30	14	44
^{136}Cs	0.14	5.5	2.5	8.0
^{137}Cs	0.53	21	9.5	31
^{140}Ba	0.13	5.0	2.3	7.3
^{141}Ce	0.37	15	6.6	21
^{144}Ce	4.2	165	74	240
^{238}Pu	5 320	211 000	95 000	306 000
^{239}Pu	5 790	229 000	103 000	332 000
^{240}Pu	5 790	229 000	103 000	332 000
^{241}Pu	100	4 130	1 860	5 990
^{241}Am	4 860	193 000	86 700	279 000
Particulates [b]		23	10	33

a Estimated from dispersion relationship: $5\ 10^{-7}\ x^{-1.4}$, where x is the distance from the release point; deposition velocity = 0.002 m s^{-1}; and population density = 400 km^{-2} in local area (1-50 km) and 20 km^{-2} in the regional area (50-2,000 km).

b Weighted average for assumed representative composition: 13% each of ^{54}Mn, ^{58}Co, ^{60}Co, ^{89}Sr, ^{134}Cs, ^{137}Cs, and ^{140}Ba; 0.9% each of ^{51}Cr, ^{59}Fe, ^{65}Zn, ^{90}Sr, ^{90}Y, ^{95}Zr, ^{124}Sb, ^{136}Cs, ^{141}Ce, and ^{144}Ce.

Table 20
Committed effective doses per unit intake by ingestion of natural radionuclides
[I5]

Radionuclide	*Fractional absorption*	*Effective dose per unit intake (nSv Bq^{-1})*		
		Infants [a]	*Children* [b]	*Adults* [c]
^{3}H (water)	1.0	0.048	0.023	0.018
^{3}H (organic)	1.0	0.12	0.057	0.042
^{7}Be	0.005	0.13	0.053	0.028
^{14}C	1.0	1.6	0.80	0.58
^{22}Na	1.0	15	5.5	3.2
^{40}K	1.0	42	13	6.2
^{238}U series:				
^{238}U	0.02	120	68	45
^{234}U	0.02	130	74	49
^{230}Th	0.0005	410	240	210
^{226}Ra	0.2	960	800	280
^{222}Rn [d]		23	5.9	3.5
^{210}Pb	0.2	3 600	1 900	690
^{210}Po	0.5	8 800	2 600	1 200
^{232}Th series:				
^{232}Th	0.0005	450	290	230
^{228}Ra	0.2	5 700	3 900	690
^{228}Th	0.0005	370	150	72
^{235}U series:				
^{235}U	0.02	130	71	47
^{231}Pa	0.0005	1 300	920	710
^{227}Ac	0.0005	3 100	1 500	1 100

a From 1 year to 2 years.
b More than 7 years to 12 years.
c More than 17 years.
d Ref. [N5].

Table 21
Food consumption rates by individuals [a]

Country / region	*Population*	*Consumption rate (kg a^{-1})*					
		Milk	*Grain*	*Leafy vegetables*	*Fruit/ vegetables*	*Meat*	*Total*
North Europe							
Denmark	5.11	173	80	18	150	66	487
Finland	4.87	263	73	6 [b]	169	71	582
Norway	4.16	202	65	37	120	76	500
Sweden	8.35	222	77	36	121	56	512
Central Europe							
Austria	7.56	145	66	71	136	99	517
Czechoslovakia	15.48	134	132	25	107	86	484
Germany	77.66	109	84	28	145	63	429
Hungary	10.62	185	110	25	160	80	560
Poland	37.46	160	180	20	132	67	559
Romania	22.73	150	190	40	240	86	706
Switzerland	6.49	180	99	29	230	110	648
West Europe							
Belgium	9.86	180	65	55	150	40	490
France	53.6	130	84	84	132	73	503
Ireland	3.54	163	68	40	69	50	390
Luxembourg	0.37	110	95	33	150	88	476
Netherlands	14.49	145	65	65	135	70	480
United Kingdom	55.87	163	68	40	100	71	442
South Europe							
Bulgaria	8.89	123	179	20	76	64	462
Greece	9.83	80	100	30	250	60	520
Italy	56.91	90	110	50	150	60	460
Portugal	9.94	45	125	113	105	42	430
Spain	37.3	104	88	124	132	62	510
Yugoslavia	22.49	146	146	55	128	55	530
USSR	279	332 [b]	133	37	118	63	683
West Asia							
Cyprus	0.64	83	94	87	315 [b]	83	662
Israel	3.87	120	130	140	190	60	640
Syrian Arab Rep.	8.98	70	190	30	340 [b]	22	652
Turkey	52	125	200	100	150	40	615
East Asia							
China	1046.4	5 [b]	229	29	173	30	466
India	750.9	39	183	28	89	5 [b]	344
Japan	121.0	50	193	30	180	120	573
North America							
Canada	25.4	181	93	21	301 [b]	130	726
United States	238.7	174	91	25	260	146	696
Average values [c]							
Countries of East and West Asia		25	210	30	140	25	430
Countries of Europe, USSR, and North America		200	110	40	165	85	600
World		85	170	35	150	50	490

Table 21, continued

Country / region	*Population*	*Consumption rate (kg a^{-1})*					
		Milk	*Grain*	*Leafy vegetables*	*Fruit/ vegetables*	*Meat*	*Total*
Representative values [d]							
Countries of East and West Asia		90	210	30	140	60	530
Countries of Europe, USSR and North America		150	110	40	170	85	555
World		120	170	35	150	70	545

a Population and consumption rates valid for 1986 [U4].
b Unusually high or low values.
c Average values are population-weighted results.
d Rounded, generic values (unusually high and low values excluded).

Table 22
Parameters of empirical models for transfer of ^{90}Sr and ^{137}Cs from deposition to diet to dose [a]

Pathway	*Transfer parameter*	*^{90}Sr*	*^{137}Cs*
Deposition to diet	b_1 (Bq a kg^{-1} per Bq m^{-2})	0.001	0.0038
	b_2 (Bq a kg^{-1} per Bq m^{-2})	0.001	0.0029
	b_3 (Bq a kg^{-1} per Bq m^{-2})	0.00011	0.000052
	λ' (a^{-1})	0.06	0.03
	P_{23} (Bq a kg^{-1} per Bq m^{-2})	0.0038	0.0084
Diet to body	c (Bq a kg^{-1} per Bq a kg^{-1})	17.5	
	g (Bq a kg^{-1} per Bq a kg^{-1})	3.7	
	λ_b (a^{-1})	0.13	
	P_{34} (Bq a kg^{-1} per Bq a kg^{-1})	48	2.6
Body to dose	P_{45} (nSv per Bq a kg^{-1})	290	2 500
Diet to intake [b]	P_{34} (Bq per Bq a kg^{-1})	500	500
Diet to dose	P_{45} (nSv per Bq)	28	13
Deposition to dose	P_{2345} (nSv per Bq m^{-2})	53	55

a Annual dose in a specific year is the deposition density of ^{90}Sr or ^{137}Cs in that year times the annual component of P_{23} times the annual component of P_{34} times P_{45} plus the contribution from intake in earlier years, which equals the residual body burden (for ^{90}Sr) reduced by exponential decay and removal ($e^{-\lambda b}$) times P_{45}.
b Assumes consumption intake of food of 500 kg a^{-1}.

Table 23
Transfer coefficients for radionuclides in the ingestion pathway

Radionuclide	*Deposition to diet* P_{23} *(mBq a kg^{-1} per Bq m^{-3})*	*Deposition to intake* [a] P_{234} *(Bq per Bq m^{-2})*	*Intake to dose* [b] P_{45} *(nSv Bq^{-1})*	*Deposition to dose* P_{2345} *(nSv per Bq m^{-2})*
^{51}Cr	7 [c]	0.56	0.038	0.02
^{54}Mn	25 [c]	2	0.71	1.4
^{55}Fe		6	0.33	2.0
^{59}Fe		0.76	1.8	1.4
^{58}Co	26 [c]	2.1	0.74	1.6
^{60}Co	36 [c]	2.9	3.4	9.9
^{65}Zn	45 [c]	3.6	3.9	14
^{89}Sr		0.03	2.6	0.08
^{90}Sr	3.8	1.9	28	53
^{95}Zr	1.3 [c]	0.1	0.95	0.10
^{95}Nb	0.9 [c]	0.07	0.58	0.04
^{124}Sb	13 [c]	1	2.5	2.5
^{131}I	0.6 [d]	0.07	61 [e]	4.3
^{134}Cs	4	2	19	38
^{136}Cs	0.6	0.3	3	0.90
^{137}Cs	8.4	4.2	13	55
^{140}Ba		0.005	2.6	0.013
^{141}Ce	0.9 [c]	0.07	0.71	0.05
^{144}Ce	1.3 [c]	0.1	5.2	0.52
^{238}Pu		0.05	230	12
^{239}Pu		0.7	250	180
^{240}Pu		0.7	250	180
^{241}Pu		0.04	4.8	0.19
^{241}Am		0.2	200	40
^{244}Cm		0.04	120	5

a May be derived from P_{23} by multiplying by total dietary consumption of 500 kg a^{-1}.
b To adults unless otherwise stated.
c To grain. To derive P_{24}, grain consumption of 80 kg a^{-1} has been assumed.
d For milk. To derive P_{24}, milk consumption of 0.3 l d^{-1} has been assumed.
e Population-weighted value.

Table 24
Annual components of dose from ingestion exposure to radionuclides following a single deposition event

Year following deposition	*Annual effective dose per unit deposition density (nSv per Bq m^{-2})*					
	^{131}I	^{140}Ba	^{89}Sr	^{55}Fe [a]	^{90}Sr	^{137}Cs
1	4.2	0.013	0.08	1.00	6.15	24.7
2			0.0005	0.60	7.73	19.2
3				0.089	2.47	0.32
4				0.069	2.30	0.31
5				0.054	2.14	0.30
6				0.042	1.99	0.29
7				0.033	1.86	0.28
8				0.025	1.73	0.27
9				0.020	1.62	0.27
10				0.015	1.51	0.26
Total						
1-10	4.2	0.013	0.08	1.95	29.5	46.2
11-20				0.049	10.7	2.2
21-50				0.004	10.3	3.7
51-100					1.9	2.0
101-∞					0.10	0.49
Commitment						
1-∞	4.2	0.013	0.08	2.0	53	55

a A transfer model does not exist. Using ^{137}Cs as a guide, it is assumed that 50% of commitment arises in first year after deposition, 30% in second year, and remainder at uniform rate over the mean life of ^{55}Fe.

Table 25
Estimates of collective dose from ingestion exposure per unit release of radionuclides from nuclear fuel cycle installations

Radionuclide	*Transfer coefficient P_{2345} (nSv per Bq m^{-2})*	*Collective effective dose per unit release (man Sv PBq^{-1}) [a]*		
		Local	*Regional*	*Total*
^{3}H [b]		1.1	1.0	2.1
^{14}C [b]		190	80	270
^{51}Cr	0.021	0.8	0.4	1.2
^{54}Mn	1.4	56	25	82
^{55}Fe	2.0	79	36	110
^{59}Fe	1.4	54	24	79
^{58}Co	1.6	62	28	89
^{60}Co	9.9	390	180	570
^{65}Zn	14	560	250	810
^{89}Sr	0.078	3.1	1.4	4.5
^{90}Sr	53	2 110	950	3 060
^{95}Zr	0.10	3.8	1.7	5.5
^{124}Sb	2.5	99	45	144
^{131}I	4.3	170	76	250
^{134}Cs	38	1 510	680	2 180
^{136}Cs	0.90	36	16	52
^{137}Cs	55	2 160	970	3 140
^{140}Ba	0.013	0.5	0.2	0.7
^{141}Ce	0.050	2.0	0.9	2.9
^{144}Ce	0.52	21	9.3	30
^{238}Pu	12	460	210	660
^{239}Pu	180	6 930	3 120	10 100
^{240}Pu	180	6 930	3 120	10 100
^{241}Pu	0.19	7.6	3.4	11
^{241}Am	40	1 580	710	2 300
Particulates [c]		570	260	830

a Population density: local (1-50 km): 400 persons km ^{2}; regional (50-200 km) 20 persons km $^{-2}$.
b Doses estimated using specific-activity model.
c Weighted average for assumed representative composition: 13% each of ^{54}Mn, ^{58}Co, ^{60}Co, ^{89}Sr, ^{134}Cs, ^{137}Cs, and ^{140}Ba; 0.9% each of ^{51}Cr, ^{59}Fe, ^{65}Zn, ^{90}Sr, ^{90}Y, ^{95}Zr, ^{124}Sb, ^{136}Cs, ^{141}Ce, and ^{144}Ce.

Table 26
Population densities surrounding nuclear fuel cycle installations

Country / region	*Area*	*Population density surrounding nuclear fuel cycle sites (inhabitants km^{-2})*		
		Uranium mining	*Fuel fabrication*	*Reactors*
World average [a]	Local [b]	3		400
	Regional [c]	25	25	20

a Representative values used in UNSCEAR assessments.
b 0-100 km for mining; 0-50 km for reactors.
c 100-2,000 km for mining and fuel fabrication; 50-2,000 km for reactors.

Table 27
Collective dose per unit release of radionuclides in liquid effluents to fresh water

Radio-nuclide	*Half-life*	*Time integral of unit activity in water* [a] *(Bq a)*	*Drinking water treatment removal factor*	*Concentration factor for fish* [b] *(Bq kg^{-1} fish per Bq l^{-1} water)*	*Dose per unit activity ingested (nSv Bq^{-1})*	*Collective dose per unit activity released (man Sv PBq^{-1})*		
						Drinking water	*Fish*	*Total*
^{3}H	12.26 a	3.90	1	1	0.018	1.3	0.003	1.3
^{14}C	5 730 a	5.00	1	50 000	0.58	54	6 690	6 740
^{24}Na	14.36 h	0.0024	0.5	20	0.43	0.009	0.0009	0.010
^{35}S	87.5 d	0.32	0.5	800	0.13	0.39	1.6	1.9
^{45}Ca	162.2 d	0.57	0.5	20	0.71	3.7	0.37	4.1
^{51}Cr	27.7 d	0.11	0.5	200	0.038	0.038	0.038	0.075
^{54}Mn	312.1 d	0.99	0.5	400	0.71	6.5	13	19
^{55}Fe	2.73 a	2.20	0.5	200	0.33	6.7	6.7	13
^{57}Co	271.8 d	0.88	0.5	300	0.21	1.7	2.6	4.3
^{58}Co	70.8 d	0.27	0.5	300	0.75	1.8	2.8	4.6
^{59}Fe	44.5 d	0.17	0.5	200	1.8	2.8	2.8	5.6
^{60}Co	5.271 a	3.02	0.5	300	3.4	95	140	240
^{65}Zn	244.3 d	0.81	0.5	1 000	3.9	29	150	180
^{89}Sr	50.5 d	0.19	0.5	60	2.6	4.6	1.4	6.0
^{90}Sr	28.78 a	4.46	0.5	60	28	1 150	350	1 500
^{95}Zr	64.02 d	0.24	0.5	300	0.96	2.1	3.2	5.3
^{95}Nb	34.98 d	0.13	0.5	300	0.59	0.73	1.1	1.8
^{97}Zr	16.9 h	0.0028	0.5	300	2.1	0.054	0.081	0.13
^{99}Mo	2.75 d	0.011	0.5	10	0.6	0.060	0.003	0.063
^{103}Ru	39.26 d	0.15	0.5	10	0.73	1.0	0.051	1.1
^{106}Ru	373.6 d	1.14	0.5	10	7.0	74	3.7	77
^{110m}Ag	249.8 d	0.82	0.5	5	2.8	21	0.53	22
^{113}Sn	115.1 d	0.42	0.5	3 000	0.73	2.8	42	45
^{122}Sb	2.73 d	0.011	0.5	100	1.7	0.17	0.084	0.25
^{124}Sb	60.2 d	0.23	0.5	100	2.5	5.2	2.6	7.9
^{125}Sb	2.76 a	2.22	0.5	100	1.1	23	11	34
^{129}I	1.6 10^{7} a	5.00	0.8	40	110	8 120	1 020	9 140
^{131}I	8.02 d	0.032	0.8	40	22	10	1.3	12
^{132}Te	3.2 d	0.013	0.5	400	3.8	0.44	0.89	1.3
^{133}I	20.8 h	0.0034	0.8	40	4.3	0.22	0.027	0.24
^{135}I	6.57 h	0.0011	0.8	40	0.93	0.015	0.002	0.017
^{134}Cs	2.06 a	1.49	0.2	2 000	19	100	2 620	2 720
^{136}Cs	13.16 d	0.051	0.2	2 000	3.0	0.57	14	15
^{137}Cs	30.07 a	2.81	0.2	2 000	13	130	3 370	3 500
^{140}Ba	12.75 d	0.050	0.5	4	2.6	1.2	0.02	1.2
^{141}Ce	32.5 d	0.12	0.1	30	0.71	0.16	0.12	0.28
^{143}Ce	1.38 d	0.0054	0.1	30	1.1	0.011	0.008	0.019
^{144}Ce	284.9 d	0.82	0.1	30	5.2	7.9	5.9	14
^{147}Pm	2.623 a	2.15	0.1	30	0.26	1.0	0.78	1.8
^{239}Pu	24 110 a	3.00	0.1	30	250	1 380	1 040	2 420

a Time integrals of unit activity in freshwater were calculated from the empirically derived values of the mean residence times in water of ^{90}Sr and ^{137}Cs (5 and 3 years, respectively), assuming that those radionuclides with high K_d, i.e. ^{144}Ce and ^{239}Pu, behave as ^{137}Cs and the other radionuclides behave as ^{90}Sr, in both cases correcting for physical delay. The formula is: $A_0 (\tau + \lambda)^{-1}$, where A_0 is unit activity (1 Bq), τ is the reciprocal of the mean residence time, and λ is ln 2 / half-life.

b Ref. [I9].

Table 28
Collective dose per unit release of radionuclides in liquid effluents to salt water

Radio-nuclide	*Half-life*	*Time integral of unit activity in water* [a] *(Bq a)*	*Concentration factor* [b] *(Bq kg^{-1} fish per Bq l^{-1} water)*		*Dose per unit activity ingested (nSv Bq^{-1})*	*Collective dose per unit activity released (man Sv PBq^{-1})*		
			Fish	*Shellfish (crustacea)*		*Fish*	*Shellfish (crustacea)*	*Total*
^{3}H	12.26 a	2.56	1	1	0.018	0.0012	0.0002	0.0014
^{14}C	5 730 a	3.00	20 000	20 000	0.58	890	150	1 040
^{24}Na	14.36 h	0.0024	0.1	0.1	0.43	0.000003	-	0.000003
^{35}S	87.5 d	0.31	2	1	0.13	0.0021	0.0002	0.0022
^{45}Ca	162.2 d	0.53	2	5	0.71	0.019	0.0080	0.027
^{51}Cr	27.7 d	0.11	200	500	0.038	0.021	0.0086	0.029
^{54}Mn	312.1 d	0.87	400	500	0.71	6.4	1.3	7.7
^{55}Fe	2.73 a	1.70	3 000	5 000	0.33	43	12	55
^{57}Co	271.8 d	0.79	1 000	5 000	0.21	4.3	3.6	7.8
^{58}Co	70.8 d	0.26	1 000	5 000	0.75	4.9	4.1	9.1
^{59}Fe	44.5 d	0.17	3 000	5 000	1.8	23	6.4	29
^{60}Co	5.271 a	2.15	1 000	5 000	3.4	190	160	350
^{65}Zn	244.3 d	0.73	1 000	50 000	3.9	73	610	680
^{89}Sr	50.5 d	0.19	2	2	2.6	0.025	0.0042	0.029
^{90}Sr	28.78 a	2.80	2	2	28	4.0	0.67	4.7
^{95}Zr	64.02 d	0.23	20	200	0.96	0.12	0.19	0.31
^{95}Nb	34.98 d	0.13	30	200	0.59	0.060	0.067	0.13
^{97}Zr	16.9 h	0.0028	20	200	2.1	0.0030	0.0050	0.0080
^{99}Mo	2.75 d	0.011	2	10	0.6	0.0003	0.0003	0.0006
^{103}Ru	39.26 d	0.15	2	100	0.73	0.0055	0.046	0.052
^{106}Ru	373.6 d	0.99	2	100	7.0	0.36	3.0	3.3
^{110m}Ag	249.8 d	0.74	500	5 000	2.8	27	45	71
^{113}Sn	115.1 d	0.40	50 000	50 000	0.73	370	62	430
^{122}Sb	2.73 d	0.011	400	400	1.7	0.19	0.031	0.22
^{124}Sb	60.2 d	0.22	400	400	2.5	5.7	0.94	6.6
^{125}Sb	2.76 a	1.71	400	400	1.1	19	3.2	23
^{129}I	1.6 10^{7} a	3	10	10	110	85	14	99
^{131}I	8.02 d	0.031	10	10	22	0.18	0.030	0.21
^{132}Te	3.2 d	0.013	1 000	1 000	3.8	1.2	0.21	1.4
^{133}I	20.8 h	0.0034	10	10	4.3	0.0038	0.0006	0.0044
^{135}I	6.57 h	0.0011	10	10	0.93	0.0003	0.00004	0.0003
^{134}Cs	2.06 a	1.49	100	30	19	73	3.6	77
^{136}Cs	13.16 d	0.051	100	30	3.0	0.39	0.020	0.41
^{137}Cs	30.07 a	2.81	100	30	13	94	4.7	98
^{140}Ba	12.75 d	0.050	10	1	2.6	0.033	0.0006	0.034
^{141}Ce	32.5 d	0.12	50	1 000	0.71	0.11	0.37	0.49
^{143}Ce	1.38 d	0.0054	50	1 000	1.1	0.0077	0.026	0.033
^{144}Ce	284.9 d	0.82	50	1 000	5.2	5.5	18	24
^{147}Pm	2.623 a	1.67	500	1 000	0.26	5.6	1.9	7.5
^{239}Pu	24 110 a	3.50	40	300	250	900	1120	2 020

a Obtained from estimated mean residence times in water of 3 years for ^{90}Sr, ^{137}Cs and other radionuclides and 3.5 years for ^{239}Pu. The time integral of unit activity is $1/(\tau+\lambda)$, where τ is the reciprocal of the mean residence time and λ is ln2 / half-life.

b Ref. [I10].

Table 29
Collective effective dose for representative composition of particulates released from reactors in liquid effluents

Radionuclide	*Fractional release*	*Collective dose per unit release (man Sv PBq^{-1})*		*Contribution to collective dose per unit total release (man Sv PBq^{-1})*	
		Freshwater	*Saltwater*	*Freshwater*	*Saltwater*
^{58}Co	0.20	4.6	9.1	0.92	1.8
^{60}Co	0.20	240	350	47	69
^{51}Cr	0.10	0.075	0.029	0.0075	0.0029
^{131}I	0.10	12	0.21	1.2	0.021
^{137}Cs	0.10	3 500	98	350	9.8
^{24}Na	0.05	0.010	0.000003	0.0005	-
^{54}Mn	0.05	19	7.7	1.0	0.39
^{65}Zn	0.05	170	680	8.7	34
^{134}Cs	0.05	2 720	77	140	3.8
^{133}I	0.02	0.24	0.0044	0.0049	0.00009
^{55}Fe	0.01	13	55	0.13	0.55
^{59}Fe	0.01	5.6	29	0.056	0.29
^{89}Sr	0.01	6.0	0.029	0.060	0.0003
^{95}Nb	0.01	1.8	0.13	0.018	0.0013
^{110m}Ag	0.01	22	71	0.22	0.71
^{125}Sb	0.01	34	23	0.34	0.23
^{135}I	0.01	0.017	0.0003	0.0002	-
^{140}Ba	0.01	1.2	0.034	0.012	0.0003
Total	1.0			550	120
Average				330	

Table 30
Parameters of the seven-compartment model of the world hydrological cycle [N3]

Compartment		*Northern hemisphere*	*Southern hemisphere*	*World*
Volume (10^{12} m^3)				
Atmospheric water		6.33	6.67	13
Soil water [a]		45.13	21.87	67
Freshwater		95	31	126
Saline water		100	4	104
Groundwater [a]		5 624	2 726	8 350
Ocean surface [b]		11 568	15 432	27 000
Deep ocean [b]		553 980	739 020	1 293 000
Transfer rate (10^{12} m^3 a^{-1})				
Atmosphere	– Soil	66.85	32.45	99.3
	– Freshwater	0.452	0.148	0.6
	– Saline water	0.096	0.004	0.1
	– Ocean	137.1	190.3 [c]	320
Soil	– Atmosphere	45.91	22.59	68.5
	– Freshwater	19.80	9.60	29.4
	– Groundwater	17.11	8.29	25.4
Freshwater	– Atmosphere	0.75	0.25	1.0
	– Ocean	20.25	9.75	30.0
Saline water	– Atmosphere	0.48	0.02	0.5
Groundwater	– Soil	15.97	8.03	24.0
	– Freshwater	0.754	0.246	1.0
	– Saline water	0.385	0.015	0.4
Ocean	– Atmosphere	157.4 [c]	200.0	350
	– Deep ocean	685.5	914.5	1 600
Deep ocean	– Ocean	685.5	914.5	1 600

a Land surface area: 67.35% in northern hemisphere, 32.65% in southern hemisphere.
b Ocean surface area: 42.84% in northern hemisphere, 57.16% in southern hemisphere.
c Transfer of 7.4 10^{12} m^3 a^{-1} from ocean surface to atmosphere (northern hemisphere) and atmosphere to ocean surface (southern hemisphere) added to achieve balance.

Table 31
Comparison of model estimates of global collective doses from tritium released to the atmosphere

Model	*Normalized effective dose ($nSv\ PBq^{-1}$)*	*Normalized collective dose [a] ($man\ Sv\ PBq^{-1}$)*
NCRP [N3] Seven-compartment model		
30°-50° northern hemisphere	0.38	0.7
Northern hemisphere	0.13	0.67
Southern hemisphere	0.11	0.07
World	0.06	0.35
Bergmann et al. [B4]		
0°-90° northern troposphere		0.95
0°-90° southern troposphere		0.65
Whole stratosphere		0.76
Killough and Kocher [K2]		
World troposphere		0.94
Northern troposphere		1.4
30°-50° northern troposphere		2.3
Natural tritium production		
Northern hemisphere	0.27	1.5
Southern hemisphere	0.27	0.2
World	0.14	0.8

a World population: $6\ 10^{9}$.

Table 32
Results of model calculation of release of 1 PBq of tritium to the atmosphere [a]

Region	*Integrated concentrations in 70-year period ($Bq\ a\ m^{-3}$)*			
	Release to 30°-50° N latitude	*Release to northern hemisphere*	*Release to southern hemisphere*	*Release to world*
Atmosphere	24.3	6.5	5.4	3.0
Surface soil water	17.0	5.3	4.4	2.4
Freshwater	6.9	4.1	3.6	1.9
Saline water	0.12	0.12	0.10	0.055
Groundwater	0.83	0.26	0.22	0.12
Ocean surface	2.9	0.66	0.54	0.30
Deep ocean	0.059	0.014	0.011	0.0061
Man	14.7	4.9	4.3	2.3
Effective dose commitment (nSv)	0.38	0.13	0.11	0.06

a Obtained with use of seven-compartment model [N3].

Table 33
Distribution of tritium and dose from release of 1 PBq to the atmosphere of the 30°-50° N band of the northern hemisphere; results of seven-compartment model

Time after release (years)	*Activity (TBq)*								*Integrated concentration in man (Bq a m^{-3})*	*Effective dose (nSv)*	
	Atmosphere	*Surface soil water*	*Freshwater*	*Saline water*	*Groundwater*	*Ocean surface*	*Deep ocean*	*Total*		*Annual*	*Cumulative*
0	1 000	0	0	0	0	0	0	1 000			
1	2.9	75.0	63.6	0.54	60	704	39	945	10.23	0.26	0.26
2	0.90	17.8	62.9	0.53	71	664	76	893	1.43	0.037	0.30
3	0.46	5.4	51.5	0.52	71	607	108	844	0.65	0.017	0.32
4	0.33	2.6	40.4	0.50	68	550	136	798	0.41	0.011	0.33
5	0.28	1.9	31.5	0.48	65	497	158	754	0.31	0.0080	0.33
6	0.25	1.6	24.5	0.46	62	448	177	713	0.25	0.0064	0.34
7	0.22	1.4	19.2	0.44	59	403	191	674	0.20	0.0052	0.35
8	0.20	1.3	15.1	0.42	56	362	202	637	0.17	0.0043	0.35
9	0.18	1.1	11.9	0.40	53	325	211	602	0.14	0.0036	0.35
10	0.16	1.0	9.4	0.38	51	291	217	569	0.12	0.0030	0.36
15	0.09	0.60	3.28	0.30	39	167	219	430	0.054	0.0014	0.37
20	0.053	0.36	1.37	0.24	30	95	197	324	0.028	0.00072	0.37
25	0.031	0.21	0.67	0.18	22	55	166	245	0.016	0.00041	0.37
30	0.018	0.13	0.37	0.14	17	32	135	184	0.0093	0.00024	0.38
35	0.011	0.082	0.22	0.11	13	18	108	139	0.0057	0.00015	0.38
40	0.0064	0.052	0.13	0.09	10	11	84	105	0.0036	0.000092	0.38
45	0.0039	0.034	0.08	0.07	7.2	6.5	65	79	0.0023	0.000059	0.38
50	0.0024	0.023	0.06	0.05	5.4	3.9	50	60	0.0015	0.000039	0.38
55	0.0016	0.015	0.04	0.04	4.0	2.4	39	45	0.0010	0.000026	0.38
60	0.0010	0.011	0.03	0.03	3.0	1.6	29	34	0.00070	0.000018	0.38
65	0.00068	0.0074	0.02	0.02	2.3	1.0	22	26	0.00049	0.000013	0.38
70	0.00047	0.0053	0.01	0.02	1.7	0.7	17	19	0.00035	0.000009	0.38
Total									14.7	0.38	

Table 34
Results of model calculation of the release of 1 PBq of ^{14}C to the environment
[T1]

Year	*Inventory of ^{14}C (TBq)*		*Inventory of stable carbon (10^{12} g) ground vegetation* [a]	*Integrated specific activity (Bq g^{-1})*			*Effective dose (μSv)*	
	Atmosphere	*Ground vegetation*		*Atmosphere* [b]	*Ground vegetation* [b]	*Ground vegetation* [a]	*Annual dose* [a]	*Cumulative dose* [a]
Release to atmosphere								
1	885	18.6	69 100	0.00059	0.00013	0.00013	0.0076	0.0076
2	712	40.4	69 300	0.0017	0.00056	0.00056	0.024	0.032
5	437	46.4	70 000	0.0039	0.0026	0.0026	0.038	0.13
10	253	28.7	70 900	0.0061	0.0053	0.0052	0.024	0.27
20	137	13.9	71 800	0.0085	0.0081	0.0080	0.011	0.41
50	76.3	7.18	73 200	0.012	0.012	0.012	0.0056	0.61
100	50.0	4.65	74 500	0.017	0.016	0.016	0.0035	0.85
200	33.0	3.05	76 000	0.022	0.022	0.021	0.0023	1.1
500	21.1	1.94	78 500	0.032	0.032	0.030	0.0014	1.6
1 000	16.3	1.50	80 400	0.045	0.045	0.040	0.0011	2.1
2 000	13.7	1.26	82 300	0.064	0.064	0.057	0.00086	3.0
5 000	9.41	0.866	84 400	0.11	0.11	0.095	0.00058	4.9
10 000	5.02	0.462	84 600	0.16	0.16	0.13	0.00031	6.9
20 000	1.43	0.131	83 900	0.20	0.20	0.17	0.000088	8.5
50 000	0.033	0.0030	82 000	0.22	0.22	0.18	0.000002	9.2

Year	*Inventory of ^{14}C (TBq)*		*Inventory of stable carbon (10^{12} g) ground vegetation* [a]	*Integrated specific activity (Bq g^{-1})*			*Effective dose (μSv)*	
	Ocean surface	*Ground vegetation*		*Ocean surface* [b]	*Ground vegetation* [b]	*Ground vegetation* [a]	*Annual dose* [a]	*Cumulative dose* [a]
Release to ocean surface								
1	977	0.124	69 100	0.00047	0.00000	0.000001	0.00005	0.00005
2	914	0.69	69 300	0.0014	0.00001	0.00001	0.00033	0.00050
5	777	3.2	70 000	0.0038	0.00009	0.00009	0.0016	0.0050
10	599	5.6	70 900	0.0071	0.00041	0.00040	0.0035	0.022
20	368	6.3	71 800	0.012	0.0013	0.0012	0.0047	0.067
50	137	4.6	73 200	0.019	0.0036	0.0035	0.0042	0.18
100	81	3.5	74 500	0.024	0.0066	0.0062	0.0031	0.32
200	53	2.6	76 000	0.030	0.011	0.010	0.0023	0.53
500	30	1.8	78 500	0.042	0.021	0.019	0.0016	1.0
1 000	23	1.4	80 400	0.055	0.032	0.029	0.0012	1.5
2 000	19	1.2	82 300	0.075	0.052	0.045	0.0009	2.4
5 000	14	0.90	84 400	0.12	0.098	0.083	0.0007	4.3
10 000	7.0	0.46	84 600	0.17	0.15	0.12	0.0005	6.3
20 000	2.0	0.13	83 900	0.21	0.19	0.16	0.0002	7.9
50 000	0.046	0.0030	82 000	0.24	0.22	0.18	0.00005	8.6

a Assuming variable inventory of carbon in environment as a result of input from burning of fossil fuels.
b Assuming fixed inventories of carbon in the environment: 750 10^{15} g (atmosphere); 1,050 10^{15} g (Atlantic Ocean surface) and 69 10^{15} g (ground vegetation).

Table 35
Estimates of collective dose to the world population per unit release of ^{129}I to different environmental compartments calculated using a global circulation model
[T1]

Time (years)	*Collective effective dose per unit release (man Sv TBq^{-1})*				
	Release to land atmosphere	*Release to ocean atmosphere*	*Release to ocean mixed layer*	*Release to deep ocean*	*Release to solid soil*
1	67.1	13.9	0.00432	0.0000036	0.0292
2	81.7	19.3	0.0158	0.000032	0.0977
5	81.8	19.4	0.0420	0.000288	0.305
10	82.0	19.4	0.0649	0.00106	0.649
20	82.4	19.5	0.0804	0.00313	1.34
50	83.4	19.8	0.0908	0.00996	3.40
100	85.1	20.2	0.104	0.0216	6.80
200	88.4	21.0	0.130	0.0453	13.5
500	98.0	23.3	0.212	0.121	32.9
1 000	113	26.9	0.361	0.259	62.9
2 000	138	33.2	0.698	0.577	115
5 000	192	46.8	1.94	1.78	223
10 000	236	59.0	4.43	4.24	309
20 000	263	69.5	9.82	9.62	359
50 000	282	85.6	25.0	24.8	382
100 000	303	106	45.8	45.6	403
1 000 000	450	254	193	193	551
10 000 000	643	446	385	385	744
100 000 000	727	530	469	469	828

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ANNEX B

Exposures from natural radiation sources

CONTENTS

INTRODUCTION

1. The exposure of human beings to ionizing radiation from natural sources is a continuing and inescapable feature of life on earth. For most individuals, this exposure exceeds that from all man-made sources combined. There are two main contributors to natural radiation exposures: high-energy cosmic ray particles incident on the earth's atmosphere and radioactive nuclides that originated in the earth's crust and are present everywhere in the environment, including the human body itself. Both external and internal exposures to humans arise from these sources. These exposures were reviewed in previous reports of the Committee, the most recent being the UNSCEAR 1993 Report [U3].

2. In assessing exposures to the natural radiation background, the Committee has considered the properties of the sources and the transport of both radionuclides and radiation in the environment. Estimates have been made of typical exposures to the world population and the range of the components of such exposures under various environmental conditions, and note has been taken of the unusually high natural radiation exposures that occur in some locations. This information has been combined with relevant dosimetric quantities to estimate the absorbed doses in tissues and the effective doses from the various sources of exposure.

3. In this Annex, the Committee continues its general review of the various components of the natural radiation background. To broaden the database, an attempt has been made to gather representative levels of exposure in as many countries as possible. Many scientists and representatives of national institutions have responded to the questionnaire on natural radiation exposures, UNSCEAR Survey of Natural Radiation Exposures, which was widely distributed by the Committee. Respondents to the questionnaire are listed in Part A of the References. The Committee acknowledges with appreciation their useful contributions to its work.

4. The database on natural radiation exposures has become extensive enough to allow quite detailed analysis. For example, the distributions of populations within various dose intervals from the different components of exposure can be examined within and between countries. The processes giving rise to the exposures can be better described and the time and geographic variations more accurately evaluated, allowing some issues to be addressed in greater detail. There remain, however, some questions that are not yet satisfactorily resolved. For example, there are difficulties in evaluating cosmic ray exposures in aircraft because of the complex neutron and ionizing radiation fields, and the dosimetry of inhaled radon is complicated by the complexities and variations of the interacting factors and processes involved.

5. Many exposures to natural radiation sources are modified by human practices. In particular, natural radionuclides are released to the environment in mineral processing and uses, such as phosphate fertilizer production and use and fossil fuel combustion, causing enhanced natural radiation exposures. In a few cases, for example, by paving roads or building houses over water, radiation exposures may be decreased, but these seem to be rather isolated cases. The general topic of enhanced exposures from natural radiation sources was considered in detail in the UNSCEAR 1982 Report [U6], and some aspects were further evaluated in the UNSCEAR 1988 and 1993 Reports [U3, U4]. The topic is discussed further, with updated information, in Chapter III of this Annex. Many persons are also exposed to enhanced levels of natural radiation at their places of work. Such workers include underground miners, some workers involved in processing of minerals, and aircraft flight crew. Occupational radiation exposures from both man-made and natural sources are considered in Annex E, "*Occupational radiation exposures*".

6. The broad relevance of natural background exposures to the world population makes the evaluations of this Annex particularly pertinent. For most individuals, the natural background exposures are much more significant than the exposures caused by man-made sources. Exceptions that apply to certain individuals are some exposures caused by medical radiation procedures, through mishandling of radiation sources, in accidents allowing radionuclides to be released to the environment, and at some workplaces. In all cases, however, the natural background source forms the baseline upon which all other exposures are added, and it is a common level against which other exposures may be compared.

I. COSMIC RADIATION

7. The earth is continually bombarded by high-energy particles that originate in outer space. These cosmic rays interact with the nuclei of atmospheric constituents, producing a cascade of interactions and secondary reaction products that contribute to cosmic ray exposures that decrease in intensity with depth in the atmosphere, from aircraft altitudes to ground level. The cosmic ray interactions also produce a number of radioactive nuclei known as cosmogenic radionuclides. Best known of these are ^{3}H and ^{14}C. Exposures from cosmic rays and from cosmogenic radionuclides are considered in this Chapter.

A. COSMIC RAYS

8. Galactic cosmic rays incident on the top of the atmosphere consist of a nucleonic component, which in

aggregate accounts for 98% of the total, and electrons, which account for the remaining 2%. The nucleonic component is primarily protons (88%) and alpha particles (11%), with the remainder heavier nuclei [G11]. These primary cosmic particles have an energy spectrum that extends from 10^8 eV to over 10^{20} eV. Below 10^{15} eV the shape of the energy spectrum can be represented by a power function of the form $E^{-2.7}$, where E is expressed in eV. Above that point, known as the knee, the spectrum steepens to a power of −3. The highest energy thus far measured is 3.2 10^{20} eV, which was inferred from ground measurements of the resulting cascade interactions in the atmosphere [O7].

9. It is thought that all but the highest energy cosmic rays that reach earth originate within the earth's own galaxy. The sources and acceleration mechanisms that create cosmic rays are uncertain, but one possibility recently substantiated by measurements from a spacecraft [K16] is that the particles are energized by shock waves that expand from supernova. The particles are confined and continually deflected by the galactic magnetic field. They become isotropic in direction, and the flux is fairly constant in time.

10. Beyond 10^{15} eV, protons may begin to escape the galactic confinement. This leaves relatively greater proportions of heavier nuclei particles in the composition of cosmic rays above this energy level. Protons with energies greater than 10^{19} eV would not be significantly deflected by the intergalactic magnetic field. The fact that protons of such high energy are also observed to be isotropic and not aligned with the plane of the galactic disk suggests that they are probably of extragalactic origin [C7]. Only astrophysical theories can suggest the origins of these ultra-high-energy cosmic rays.

11. Another component of cosmic rays is generated near the surface of the sun by magnetic disturbances. These solar particle events are comprised mostly of protons of energies generally below 100 MeV and only rarely above 10 GeV (10^{10} eV). These particles can produce significant dose rates at high altitudes, but only the most energetic affect dose rates at ground level. Solar particle events can, in addition, disturb the earth's magnetic field in such a way as to change the galactic particle intensity. The events are of short duration, typically a few hours, and highly variable in intensity. They have a negligible impact on long-term doses to the general population.

12. The most significant long-term solar effect is the 11-year cycle in solar activity, which generates a corresponding cycle in total cosmic radiation intensity. The periodic variation in solar activity produces a similar variation in the solar wind. The solar wind is a highly ionized plasma with associated magnetic field, and it is the varying strength of this field that modulates the intensity of galactic cosmic radiation. At times of maximum solar activity the field is at its highest and the galactic cosmic radiation intensity is at its lowest.

13. The magnetic field of the earth partly reduces the intensity of cosmic radiation reaching the top of the atmosphere, the form of the earth's field being such that only particles of higher energies can penetrate at lower geomagnetic latitudes. This produces the geomagnetic latitude effect, with minimum intensities and dose rates at the equator and maximum near the geomagnetic poles.

14. The high-energy particles incident on the atmosphere interact with atoms and molecules in the air and generate a complex set of secondary charged and uncharged particles, including protons, neutrons, pions and lower-Z nuclei. The secondary nucleons in turn generate more nucleons, producing a nucleonic cascade in the atmosphere. Because of their longer mean free path, neutrons dominate the nucleonic component at lower altitudes. As a result of the various interactions, the neutron energy distribution peaks between 50 and 500 MeV; a lower energy peak, around 1 MeV, is produced by nuclear deexcitation (evaporation). Both components are important in dose assessment.

15. The pions generated in nuclear interactions are the main source of the other components of the cosmic radiation field in the atmosphere. The neutral pions decay into high-energy photons, which produce high-energy electrons, which in turn produce photons etc., thus producing the electromagnetic, or photon/electron, cascade. Electrons and positrons dominate the charged particle fluence rate at middle altitudes. The charged pions decay into muons, whose long mean free path in the atmosphere makes them the dominant component of the charged-particle flux at ground level. They are also accompanied by a small flux of collision electrons generated along their path.

16. The changing components of dose rate caused by the secondary cosmic ray constituents in the atmosphere are illustrated in Figure I. At ground level, the muon component is the most important contributor to dose; at aircraft altitudes, neutrons, electrons, positrons, photons, and protons are the most significant components. At higher altitudes, the heavy nuclei component must also be considered.

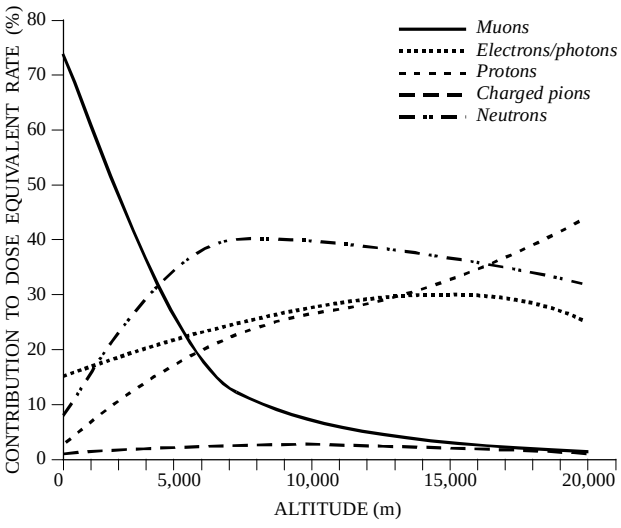

Figure I. Components of the dose equivalent rate from cosmic rays in the atmosphere [O4].

17. The cosmic radiation intensity in the atmosphere has been measured in increasing detail in recent years. A complete mapping of the cosmic radiation field and the determination of exposure conditions and doses throughout the atmosphere as a function of time can be based on these measurements with appropriate interpolation or by the application of reliable radiation transport codes. Codes have been developed for this purpose [O1, W3], and transport codes for accelerator shielding applications have been adapted [K18, P17, R19]. Their adequacy has been, and is currently being, tested against the available measurements.

18. Since the publication of the UNSCEAR 1993 Report [U3], some new information has been added to the database on which the exposure of the general population to cosmic radiation at ground level is based. In particular, both the low- and high-energy peaks in the neutron energy distribution are recognized, and instrumentation has been developed that responds to the extended energy range. This has led to modified estimates of dose from this component of cosmic radiation. There has been substantial progress in recent years in the study of the cosmic radiation fields at aircraft altitudes [E1].

1. Exposure at ground level

19. At ground level, the dominant component of the cosmic-ray field is muons with energies mostly between 1 and 20 GeV. These contribute about 80% of the absorbed dose rate in free air from the directly ionizing radiation; the remainder comes from electrons produced by the muons or present in the electromagnetic cascade. In the early literature, these two components of the charged particle flux were referred to as the "hard" and "soft" components, respectively, because the electrons are much more readily absorbed by any shielding. As altitude increases, the electrons become more important contributors to the dose rate.

20. Many measurements have been made of the altitude profile of the charged-particle and photon ionization and the absorbed dose rate in free air at ground level. A review of this information in the UNSCEAR 1988 Report [U4] indicated that a representative value for this dose rate at sea level is 32 nGy h^{-1}. The geomagnetic latitude effect is about 10%, so that a value of 30 nGy h^{-1} is appropriate for latitudes below 30°. Considering that a large fraction of the world population lives at latitudes below 30° (50% in the northern hemisphere, 85% in the southern hemisphere, and 54% overall), the population-weighted average absorbed dose rate from the directly ionizing and photon components of cosmic radiation at sea level corresponds to 31 nGy h^{-1}, although it is not known to this precision. The dose rate values may be considered as averages over the 11-year solar activity cycle, with the total range of variation about 10%. Since mostly muons are involved, a radiation weighting factor of unity is appropriate [I1], yielding the same values for the effective dose rate, i.e. 31 nSv h^{-1} or 270 μSv a^{-1}.

21. It is much more difficult to estimate the neutron contribution to effective dose rate at sea level. Although available data on neutron fluences and energy distributions are sparse, recent measurements and calculations are beginning to provide clarification. Because earlier instrumentation had a low response to high-energy neutrons, which are an important component of the spectrum, some increases in the estimates of the fluence rate and effective dose rate are being suggested. Measurements [R19, S10] made at the top of the Zugspitze mountain in Germany (altitude 2,963 m, atmospheric depth 718 g cm^{-2}) and associated calculations gave a fluence rate of 0.126 ± 0.01 cm^{-2} s^{-1} [S48]. Attenuation with altitude was described using the function $e^{-0.00721p}$, where p (g cm^{-2}) is the atmospheric depth. From this, a fluence rate at sea level (p = 1,033 g cm^{-2}) of 0.0122 ± 0.001 cm^{-2} s^{-1} can be derived. A value of 0.0133 ± 0.001 $cm^{-2}s^{-1}$ was determined at about sea level for a geomagnetic latitude of 53°N near Braunschweig in Germany [A15] and a value of 0.0123 cm^{-2} s^{-1} at sea level for a geomagnetic latitude of 45°N in Hampton, Virginia, in the United States [G20]. Earlier measurement results were 0.008 cm^{-2} s^{-1} [H16, H17].

22. The effective dose rate (resulting from isotropic incidence) at a fluence rate of 0.013 cm^{-2} s^{-1}, obtained by applying a neutron fluence energy distribution weighting factor of 200 pSv cm^2 (equal to 720 nSv h^{-1} per neutron cm^{-2} s^{-1}), is 9 nSv h^{-1} [S48]. The shape of the neutron energy spectrum at habitable altitudes is considered to be relatively invariant, and therefore the fluence to effective dose (isotropic) conversion coefficient is expected to be generally valid. On this basis, the annual effective dose rate from neutrons at sea level and at 50° latitude is estimated to be 80 μSv a^{-1}.

23. Birattari et al. [B19], using a remmeter with an extended range, reported a value corresponding to 80 μSv a^{-1} (±5%), which is in agreement with the estimate derived in the preceding paragraph. From a series of measurements by Burgkhardt et al. [B18] and Gaborit et al. [G16], the sea level effective dose rate from neutrons was determined to be 60 μSv a^{-1}, but these results are probably underestimates, because the instrumentation lacked response to the high-energy component.

24. Incoming protons that initiate the cosmic ray neutron field are strongly affected by the earth's magnetic field, with the effect that the neutron fluence rate in equatorial regions is less than that in polar regions. Investigators have recognized the importance of the latitude effect, but it has not been carefully quantified by reliable measurements. Florek et al. [F14], quoting results of the Los Alamos LAHET code system calculation, suggest that the equatorial neutron fluence rate at sea level is one fifth the polar rate and that the rate at 50° latitude is 80% of the polar rate. Nakamura et al. [N20], combining measurements made at Tokyo (24°N) with those for higher latitudes [H16, H17], obtained a narrower range for the pole to equator variation, i.e. the equatorial rate about one fourth of the polar rate.

25. An approximate analysis of the latitude effect for cosmic ray neutrons at sea level is presented in Figure II. The normalization points are the measurement results of Birattari et al. [B19] at 50°N (9 nSv h^{-1} = 80 μSv a^{-1}) and of Nakamura et al. [N20] at 24°N (4 nSv h^{-1} = 35 μSv a^{-1}). The maximum value is estimated to be roughly 11 nSv h^{-1} (9 nSv h^{-1} ÷ 0.8). The resultant curve may be used to infer the values for 10° latitude bands to be used in deriving a population-weighted average (Table 1). The world average effective dose rate at sea level from cosmic ray neutrons thus determined is 5.5 nSv h^{-1} or 48 μSv a^{-1}.

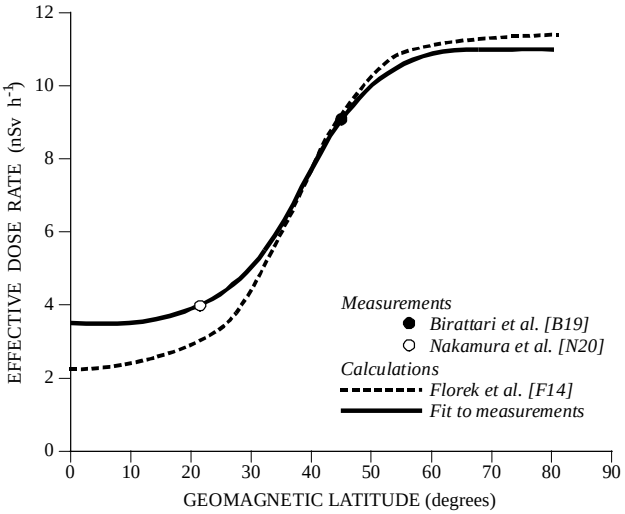

Figure II. Latitude variation in dose rate from cosmic ray neutrons at sea level.

26. For both the directly ionizing and photon component and the neutron component of cosmic rays, there is a substantial altitude effect. Bouville and Lowder [B1] used both measurements and calculations to derive expressions of the altitude dependence of cosmic ray dose rates at habitable locations. These relationships were given in the UNSCEAR 1993 Report [U3] (see also Annex A, "*Dose assessment methodologies*"). Combining these altitude dependence relationships with their analysis of the altitude distribution of the world population, these investigators derived estimates of the population-weighted average dose rates. For the directly ionizing and photon component the population-weighted average dose rate is 1.25 times that at sea level, and for neutrons 2.5 times. Some two thirds of the world population lives in coastal regions, but because dose rates increase with altitude, populations at high altitudes contribute proportionately more to the weighted average. The population-weighted average value corresponds to the dose rate that occurs at 900 m above sea level. The calculations cited by Florek et al. [F14] and the attenuation factor used in paragraph 21 indicate that the effective dose rate from neutrons would increase by a factor of 2.1 between sea level and 900 m elevation, in general agreement with the results of Bouville and Lowder [B1], which were also based on analysis of calculated altitude changes in the dose rate [O3].

27. From estimates derived above, the latitude- and altitude-averaged cosmic ray dose rates may be derived. For the directly ionizing and photon component, the world average effective dose rate is 340 μSv a^{-1} (31 nSv h^{-1} or 270 μSv a^{-1} multiplied by the altitude factor of 1.25); for the neutron component, the average value is 120 μSv a^{-1} (48 μSv a^{-1} multiplied by the altitude factor of 2.5). These results apply to exposures outdoors.

28. The rather limited data on the shielding effect of buildings on cosmic radiation charged particles and photons were summarized in the UNSCEAR 1988 and 1993 Reports [U3, U4]. Observed shielding factors ranged from close to 1 for minimal vertical shielding, e.g. a small wooden house, to 0.4 for lower storeys of substantial concrete buildings. This is consistent with the classical ion chamber observations that defined the "soft" component. These observations imply that a factor of 0.8 would be appropriate after the radiation has passed through a substantial ceiling. In any case, values for particular structures depend on both construction and design, and only broad generalizations can be made. There appears to be no need to change the representative value of the shielding factor, 0.8, used in previous reports.

29. In its previous assessments, the Committee did not apply a shielding factor to the neutron component of cosmic radiation, because of the uncertain balance between attenuation and secondary build-up of neutrons passing through building materials. Although this issue still awaits evaluation, it seems likely that 10%–20% attenuation could be reasonably expected.

30. From the above considerations, the Committee estimates the world average effective dose from the directly ionizing and photon component of cosmic rays to be 280 μSv a^{-1} (applying the indoor shielding factor of 0.8 and assuming indoor occupancy to be 80% of time). The corresponding average value for the neutron component (applying the same adjustment factors) is 100 μSv a^{-1}. The component estimates have been altered slightly from the earlier estimates (300 μSv a^{-1} and 80 μSv a^{-1}) [U3], but the total of 380 μSv a^{-1} remains unchanged. The average annual dose rates for the hemispheres and the world are summarized in Table 2.

31. The global value of the annual collective effective dose is about 2 10^6 man Sv. About one half of this dose is received by the two thirds of the population that lives at altitudes below 0.5 km. The approximately 2% of the population living above 3 km receives a disproportionate 10% of the collective dose. The average annual effective doses from cosmic rays for some high-altitude cities were listed in the UNSCEAR 1993 Report [U3]. Between sea level and 4 km, the neutron contribution to the cosmic radiation effective dose increases from 8% to 35% of the total. Overall, the range of annual average effective doses to the world population is 300–2,000 μSv, with a population-weighted average of 380 μSv.

2. Exposures at aircraft altitudes

32. Aircraft passengers and crew are subject to cosmic radiation exposure rates much higher than the rates at ground level. Total exposure on a given flight depends on the particular path taken through the atmosphere in terms of

altitude (pressure rather than radar altitude) and geomagnetic latitude, as well as on the speed of the aircraft; that is, it depends on the duration of exposure at various altitudes and latitudes. Complicating the situation is the fact that the exposure associated with any flight path may vary with time. There are two possible approaches to dose assessment under these circumstances: (a) area and/or individual monitoring for each flight and (b) determining the radiation fields as a function of time and space and calculating the effective dose for any flight path. Both approaches are being taken, and further measurements and results of calculations are becoming available [E1]

33. Duration of exposure is obviously an important factor in the assessment of doses to passengers and crew. Flight durations for crew members are expressed as the time between leaving the terminal before takeoff and returning after landing. Thus the exposure includes those accrued on the ground and those accrued at all altitudes up to cruising altitude. For flights of more than one hour, the exposure rate at cruising altitude will be the main determinant of dose. The annual number of hours flown by crew members varies from individual to individual and from airline to airline, depending on policy. The range appears to be 300–900 hours per year, with an average of about 500. For the general population, it can be inferred that there are three groups: non-flyers (0 hours), occasional flyers (3–50 hours, with an average of 10), and frequent flyers, i.e. business flyers, couriers, etc. (50–1,200 hours, with an average of 100). The vast majority of the world's population still falls into the first category.

34. Commercial subsonic aircraft generally have cruising altitudes of 7 to 12 km. Although many measurements have been made in aircraft and balloons at these altitudes, there are two major problems in using these data to estimate doses. First, each measurement or set of measurements is carried out for a particular flight path at a particular time, and generalizing such results to other paths and times is not simple. Secondly, most detectors respond to only certain components of the total field, and proper calibration of detector response is generally not simple. In addition, interpreting these data in terms of effective dose requires a knowledge of the overall properties of the complex radiation fields at these altitudes, and this knowledge is as yet incomplete. However, the data can be used as benchmarks to test the ability of existing radiation transport codes to provide reliable information on field properties and effective doses. Moreover, the data obtained by a number of different detector systems on many flights in recent years can be interpreted in terms of the operational quantity ambient dose equivalent, to an estimated accuracy of about 25% [B16, E1, O9, S46, T12].

35. Estimation of doses to passengers and crew are based on the route doses that are obtained from measurements or calculations of the effective dose rate as a function of flight parameters, using, for example, the CARI programme developed by O'Brien and Friedberg [F12, F13, O3] or a computer programme based on measurements and calculations, such as the NASA AIR model [W3] and EPCARD [S47].

36. A working group of the European Commission [E1] reviewed measurements of dose equivalent rates at aircraft altitudes mostly concentrated in the years 1974–1976, when there was minimal solar activity, and 1991, during maximum solar activity. More recent measurement results were presented at the 1998 Dublin Conference [K19]. The results clearly indicate the strong dependence of the dose equivalent rates on altitude, latitude, and the phase of solar activity. The general pattern of measurements is shown in Figure III. The report of the working group [E1] noted that the contributions of the high- and low-LET components are comparable at geomagnetic latitudes of 50° and that the exposure rate throughout the aircraft is approximately constant.

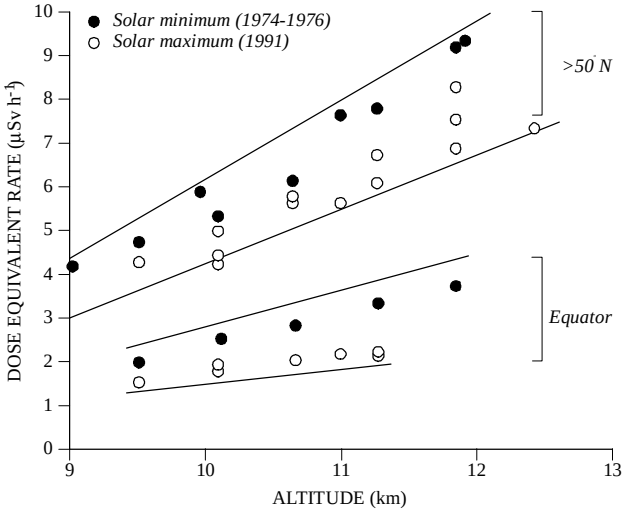

Figure III. Measurement results of cosmic ray exposure rate at aircraft altitudes [E1].

37. The results of recent measurements and recent calculations are broadly consistent. For altitudes of 9–12 km at temperate latitudes, the effective dose rates are in the range 5–8 μSv h^{-1}, such that for a transatlantic flight from Europe to North America, the route dose would be 30–45 μSv. At equatorial latitudes, the dose rates are lower and in the range of 2–4 μSv h^{-1}.

38. A small proportion of passengers and flight crews travel at higher altitudes (~18 km) on supersonic transports. Doses on board those flights are routinely determined from active monitors. Results of this monitoring were summarized in the UNSCEAR 1993 Report [U3]. Effective dose rates of 10–12 μSv h^{-1} were normally found. Recent measurements at these altitudes are in agreement [B24, C29, G21]. One potential problem for high-altitude aircraft is the possibly significant dose contribution from solar particle events. O'Brien et al. [O4] calculated that 13 solar particle events between December 1988 and July 1992 contributed only 2% and 7% of the total cosmic-ray equivalent dose at 11 and 18 km altitude, respectively. However, there is a potential for much more significant events such as the highly energetic event of February 1956. Calculated dose equivalent rates for this event at 20 km are of the order of 1 mSv h^{-1} [A2]. However, no events of this magnitude have taken place since then. It requires both high solar particle flux densities

and high energies (1 GeV) for an event to produce high dose rates at aircraft altitudes, and this is a rare occurrence.

B. COSMOGENIC RADIONUCLIDES

39. The interactions of cosmic-ray particles in the atmosphere produce a number of radionuclides, including ^{3}H, ^{7}Be, ^{14}C, and ^{22}Na. The radioactive half-lives and decay modes of these and other cosmogenic radionuclides with half-lives greater than 1 day are listed in Table 3. Essentially all nuclear species lighter than the target nuclei (primarily nitrogen, oxygen and argon) are produced by high-energy spallation interactions. Production is greatest in the upper stratosphere, but some energetic cosmic-ray neutrons and protons survive in the lower atmosphere, producing cosmogenic radionuclides there as well. Production is not only altitude- but also latitude-dependent and varies as well with the 11-year solar cycle that modulates cosmic-ray penetration through the earth's magnetic field.

40. The calculated global average production rates of cosmogenic radionuclides per unit surface area of the earth and the total annual production are listed in Table 4. The equilibrium global inventory can be derived from the latter value (production rate × 1.44 × half-life). These estimates are somewhat uncertain, as they depend on the validity of the calculational models. Estimates of the environmental distribution of cosmogenic radionuclides can be made based on equilibrium concentrations. The average concentrations in the troposphere are included in Table 4. Since the production, transfer from stratosphere to troposphere, and deposition patterns are latitude- and season-dependent, there may be wide deviations from these average values.

41. Except for ^{3}H, ^{14}C, and ^{22}Na, which are elements with metabolic roles in the human body, the cosmogenic radionuclides contribute little to radiation doses and are mainly of relevance as tracers in the atmosphere and in hydrological systems after deposition. The Committee previously assessed the annual effective doses from cosmogenic radionuclides to be 12 μSv from ^{14}C, 0.15 μSv from ^{22}Na, 0.01 μSv from ^{3}H, and 0.03 μSv from ^{7}Be [U3]. Because of the importance of ^{3}H and ^{14}C from man-made sources of radiation, the environmental and dosimetric aspects of these radionuclides are reviewed in some detail in Annex A, "*Dose assessment methodologies*".

II. TERRESTRIAL RADIATION

42. Naturally occurring radionuclides of terrestrial origin (also called primordial radionuclides) are present in various degrees in all media in the environment, including the human body itself. Only those radionuclides with half-lives comparable to the age of the earth, and their decay products, exist in significant quantities in these materials. Irradiation of the human body from external sources is mainly by gamma radiation from radionuclides in the ^{238}U and ^{232}Th series and from ^{40}K. These radionuclides are also present in the body and irradiate the various organs with alpha and beta particles, as well as gamma rays. Some other terrestrial radionuclides, including those of the ^{235}U series, ^{87}Rb, ^{138}La, ^{147}Sm, and ^{176}Lu, exist in nature but at such low levels that their contributions to the dose in humans are small. Physical data for terrestrial radionuclides are included in Table 3. The external and internal exposures from these radionuclides are evaluated in this Chapter.

A. EXTERNAL EXPOSURES

1. Outdoors

43. External exposures outdoors arise from terrestrial radionuclides present at trace levels in all soils. The specific levels are related to the types of rock from which the soils originate. Higher radiation levels are associated with igneous rocks, such as granite, and lower levels with sedimentary rocks. There are exceptions, however, as some shales and phosphate rocks have relatively high content of radionuclides. There have been many surveys to determine the background levels of radionuclides in soils, which can in turn be related to the absorbed dose rates in air. The latter can easily be measured directly, and these results provide an even more extensive evaluation of the background exposure levels in different countries. All of these spectrometric measurements indicate that the three components of the external radiation field, namely from the gamma-emitting radionuclides in the ^{238}U and ^{232}Th series and ^{40}K, make approximately equal contributions to the externally incident gamma radiation dose to individuals in typical situations both outdoors and indoors.

44. The radionuclides in the uranium and thorium decay chains cannot be assumed to be in radioactive equilibrium. The isotopes ^{238}U and ^{234}U are in approximate equilibrium, as they are separated by two much shorter-lived nuclides, ^{234}Th and ^{234}Pa. The decay process itself may, however, allow some dissociation of the decay radionuclide from the source material, facilitating subsequent environmental transfer. Thus, ^{234}U may be somewhat deficient relative to ^{238}U in soils and enhanced in rivers and the sea. The radionuclide ^{226}Ra in this chain may have slightly different concentrations than ^{238}U, because separation may occur between its parent ^{230}Th and uranium and because radium has greater mobility in the environment. The decay products of ^{226}Ra include the gaseous element radon, which diffuses out of the soil, reducing the exposure rate from the ^{238}U series. The radon radionuclide in this series, ^{222}Rn, has a half-life of only a few days, but it has

two longer-lived decay products, ^{210}Pb and ^{210}Po, which are important in dose evaluations. For the ^{232}Th series, similar considerations apply. The radionuclide ^{228}Ra has a sufficiently long half-life that may allow some separation from its parent, ^{232}Th. The gaseous element of the chain, ^{220}Rn, has a very short half-life and no long-lived decay products.

45. The results of spectrometric analyses of soil samples gathered in different countries are listed in Table 5. These are the *in situ* concentrations. If the concentrations have been reported on a dry basis, representative values of soil moisture of 30% by volume and soil density of 1.6 g cm^{-3} have been assumed. The conversion factor (dry to wet basis) is thus 0.81 (dry weight of 1 cm^3: 1.3 g; wet weight of 1 cm^3: 1.3 g soil + 0.3 g water = 1.6 g; ratio: 1.3 ÷ 1.6 = 0.81).

46. The activity concentration of ^{40}K in soil is an order of magnitude higher than that of ^{238}U or ^{232}Th. In its first assessment of representative concentrations of these radionuclides in soil, in the UNSCEAR 1982 Report [U6], the Committee suggested the values of 370, 25, and 25 Bq kg^{-1} for ^{40}K, ^{238}U and ^{232}Th, respectively. On the basis of the higher levels reported for China and the United States, the Committee revised the values for both ^{238}U and ^{232}Th to 40 Bq kg^{-1} in the UNSCEAR 1993 Report [U3]. A more recently completed country-wide survey in China indicates somewhat lower values [P1, P16]. These and the results for many more countries are included in Table 5. The median values are 400, 35, and 30 Bq kg^{-1}, and the population-weighted values are 420, 33, and 45 Bq kg^{-1} for ^{40}K, ^{238}U, and ^{232}Th, respectively. The results of applying the dose coefficients relating soil concentrations to absorbed dose rate in air [I20, S49] to these values are shown in Table 6. The population-weighted values give an average absorbed dose rate in air outdoors from terrestrial gamma radiation of 60 nGy h^{-1}.

47. Direct measurements of absorbed dose rates in air have been carried out in the last few decades in many countries of the world. The database presented in Table 7 encompasses 70% of the world population. A number of countries have been added since the previous evaluation by the Committee [U3], and several values have been revised based on new information. The population-weighted average is 59 nGy h^{-1}, compared with 57 nGy h^{-1} in the previous assessment [U3]. The average values range from 18 to 93 nGy h^{-1}. A typical range of variability for measured absorbed dose rates in air is from 10 to 200 nGy h^{-1}.

48. Of the values reported in Table 7 of the absorbed dose rate in air outdoors, the lowest are in Cyprus, Iceland, Egypt, the Netherlands, Brunei, and the United Kingdom, all less than 40 nGy h^{-1}, and the highest values are in Australia, Malaysia, and Portugal, all greater than 80 nGy h^{-1}. Exposures inferred from the soil concentration results (Table 5) generally show reasonable agreement with the measured outdoor absorbed dose rate in air (Table 8). A discrepancy of 30% or more may indicate that one or the other survey was not representative for the country. Those countries where there are considerable discrepancies include Luxembourg and Sweden, where the ^{40}K levels in soil are relatively high; Syria and Albania, where all levels of radionuclides in soil are low; and Ireland, where the outdoor measurements are rather low. The surveys were conducted by various means and with different numbers of measurements. The representativeness of each survey cannot be judged. The overall results should be reasonably indicative of the global average.

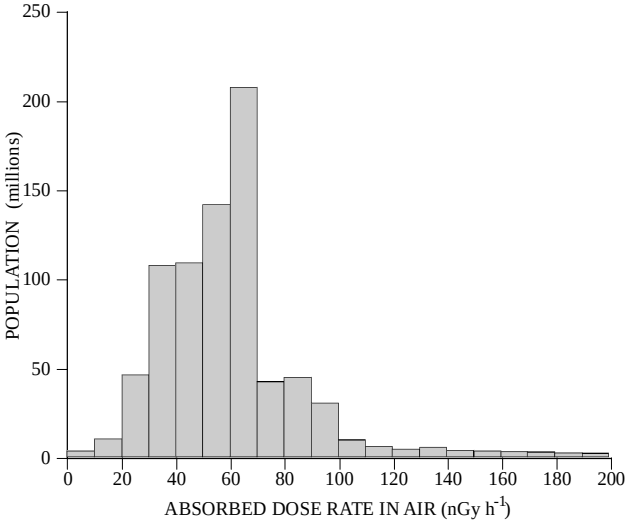

Figure IV. Distribution of population of 25 countries with respect to the outdoor absorbed dose rate in air from terrestrial gamma radiation.

49. A few countries have evaluated the distribution of the population exposed to various ranges of outdoor absorbed dose rates in air. These data, provided in response to the UNSCEAR Survey of Natural Radiation Exposures, are presented in Table 9. The median for the population included (788 million persons in the 25 countries) is in the 50–59 nGy h^{-1} range. A relatively large population group in the Russian Federation is reported to be in the 60–69 nGy h^{-1} range. Decreasing numbers of people are reported to reside in areas with higher levels of outdoor absorbed dose rate in air. The distribution of population according to this sample is presented in Figure IV.

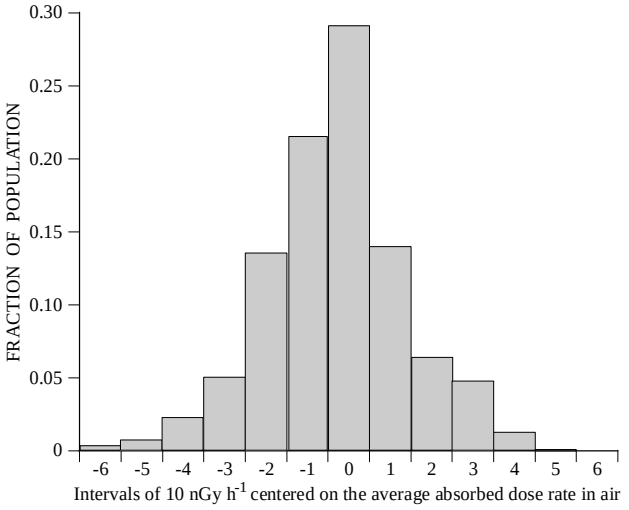

Figure V. Standardized distribution of population with respect to decades about the average absorbed dose rate in air.

50. The total population distribution presented in Figure IV is obtained by combining the data from 25 countries, each with different average outdoor levels of absorbed dose rate in air. The small sample is responsible for the somewhat uneven distribution. The distributions within countries follow a more standard pattern. This is illustrated in Figure V, the data and analysis for which are in Table 10. The distribution of population for each country is centred about a central decade of dose rate indicated as 0. In other words, the distributions are aligned about the central values. Each interval of dose rate represents a decade of dose rate values (e.g. 50–59 nGy h^{-1}). The average distribution is derived from the combined distributions.

51. The standardized distribution is centred about the average level of outdoor dose; 29% of the population is within the 10 nGy h^{-1} decade that encompasses the average value (e.g. is within 50–59 nGy h^{-1} for average outdoor levels anywhere in the range 50–59 nGy h^{-1}). Figure V shows the distribution to ±6 decades of outdoor absorbed dose rate in air. The distribution is relatively normal at levels of dose less than the average, i.e. the population groups are 22% and 14% of the total at the decades of dose from 10 to 20 nGy h^{-1} below the average. The distribution falls more sharply for outdoor levels of dose above the average, i.e. the population groups are 14% and 6% of the total at the next two decades of dose from 10 to 20 nGy h^{-1} above the average. The distribution is approximately log-normal, as shown in Figure VI.

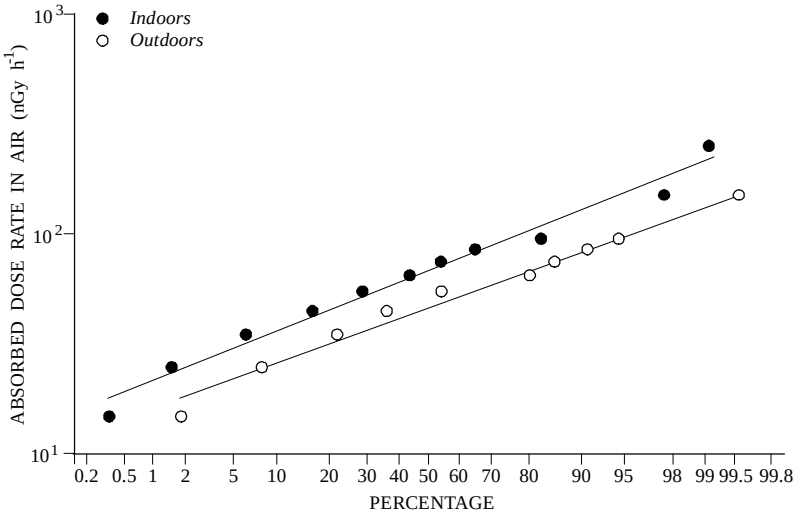

Figure VI. Cumulative distribution of population with respect to outdoor and indoor aborbed dose rate in air from terrestrial gamma radiation.

The data are from independent surveys in different countries (outdoors: Table 9; indoors: Table 12).

52. Although the standardized distribution could be used to indicate the approximate proportions of a population about an average exposure level, it would be important to know whether there are local features of geology that could lead to understandable deviations in the extremes. Extrapolation of the distribution, which is based on just over 10% of the world population, to the entire world population would not be justified, since areas of unusually low or high background levels are probably not well enough represented in the standardized distribution.

53. In addition to variations from place to place, the ambient background gamma dose rate in air at any specific location is not constant in time. It is subject to considerable fluctuation, in particular from the removal of radon progeny in air by rainfall, soil moisture and snow cover. Continuous monitoring records show variations of ±5% from the daily average level in 30-minute measurement intervals [K1, S6]. Washout and rainout of radon progeny from air may result in the short-term enhancement, by 50%–100%, of the gamma-ray dose rate in air. The extent of the elevation depends on rain interval [F2] as well as the rainfall amount. The elevated level lasts for several hours and is followed by a depression of about 5% from the average level, due to shielding from increased soil moisture. If there is no further rainfall, the return to normal occurs in hours or days as the soil saturation disappears. Snow cover depresses the background level by about 1% for each centimetre of snow [F17, H32].

54. There are small areas of markedly high absorbed dose rates in air throughout the world that are associated with thorium-bearing and uranium-bearing minerals in the soil. In those areas, absorbed dose rates in air of several hundred nanograys per hour are not uncommon. The Committee has noted the existence of these areas in all of its previous assessments of natural radiation exposures, and a series of conferences on this topic has helped to bring together the available information [C30, S57, V4, W13].

55. Areas of high natural background are listed in Table 11. There are various causes of these elevated exposure levels. Some result from monazite sand deposits, which have high levels of thorium, including Guarapari in Brazil, Yangiang in China, the states of Kerala and Madras in India, and the Nile delta in Egypt. Some have volcanic soils such as Mineas Gerais in Brazil, Niue Island in the Pacific, and parts of Italy. The central massive in France has granitic and schistic rocks and sands, and an area in the southwest of that country is one

of many associated with uranium minerals in soil. The areas of Ramsar and Mahallat in Iran and are caused by ^{226}Ra deposited from waters flowing from hot springs.

56. It should be noted that exposures in high background areas can vary in time as deposits or beach sands are replenished by springs and tides. Road construction and urbanization of these areas have led to moderate decreases in the background levels [S56, V5].

2. Indoors

57. Indoor exposure to gamma rays, mainly determined by the materials of construction, is inherently greater than outdoor exposure if earth materials have been used; the source geometry changes from half-space to a more surrounding configuration indoors. When the duration of occupancy is taken into account, indoor exposure becomes even more significant. Buildings constructed of wood add little to indoor exposures, which may then be comparable to outdoor exposures.

58. Surveys of absorbed dose rates in air inside dwellings are not as complete as outdoor surveys. The reported values are listed in Table 7. About 45% of the world population is represented in the data that are currently available. The population-weighted average is 84 nGy h^{-1} with national averages ranging from 20 to 200 nGy h^{-1}. The lowest values are in New Zealand, Iceland and the United States, all below 40 nGy h^{-1}, which probably reflects the preponderance of wood-frame houses. The highest values (95–115 nGy h^{-1}) are in Hungary, Malaysia, China, Albania, Portugal, Australia, Italy, Spain, Sweden, and Iran, which must reflect wide use of stone or masonry materials in buildings.

59. The ratios of indoor to outdoor exposure are indicated in Table 7. These are intended not to reflect actual conditions at specific locations but to give a general, relative idea of the broad data gathered in different countries. The indoor and outdoor results may have been derived in separate surveys in locations not closely coordinated. The outdoor levels generally refer to open, undisturbed ground, but sometimes street locations may have been used. The indoor to outdoor ratios range from 0.6 to 2.3, with a population-weighted value of 1.4. Thus indoor exposures (absorbed dose rate in air from terrestrial gamma radiation) are, in general, 40% greater than outdoor exposures. Values less than one are determined only for Thailand, the United States and Iceland, where wood-frame construction is common. High values of the ratio (>2) result from high levels indoors (in Sweden and Hong Kong) relative to outdoors or from low values outdoors (in the Netherlands) relative to indoors.

60. The distributions of populations with respect to indoor exposures have been assessed in several countries. The data are presented in Table 12. The distributions are more or less symmetrical in several countries, e.g. Belgium, Denmark, and Romania. Bulgaria reports a relatively narrow distribution: the population falls mostly in the central three decades of dose rate. By contrast, the distribution in Hungary is very wide, although nearly 50% of the population is in the single decade just above the mean dose rate for the country. The distribution in Italy is also wide and approximately bimodal. The distributions in the Russian Federation, Finland and Lithuania are characterized by separate peaks in the distributions at decades 2 or 3 above the country mean. These various distributions can no doubt be explained by the types of buildings in which the populations live. Data from additional surveys in other countries will be required to indicate a characteristic distribution that might be further generalized.

61. Indoor and outdoor distributions of external exposures are compared in Figure VII. Only countries for which both indoor and outdoor distributions are available (generally the smaller countries of Europe) are included. The comparison shows the shift to higher exposure rates indoors and the somewhat broader distribution of population for the indoor exposure rate. The population-weighted average exposure rates for the countries included in Figure VII are 58 nGy h^{-1} outdoors and 81 nGy h^{-1} indoors, with an indoor/outdoor ratio of 1.4, which is identical to the population-weighted average for the much larger sample of countries in Table 7.

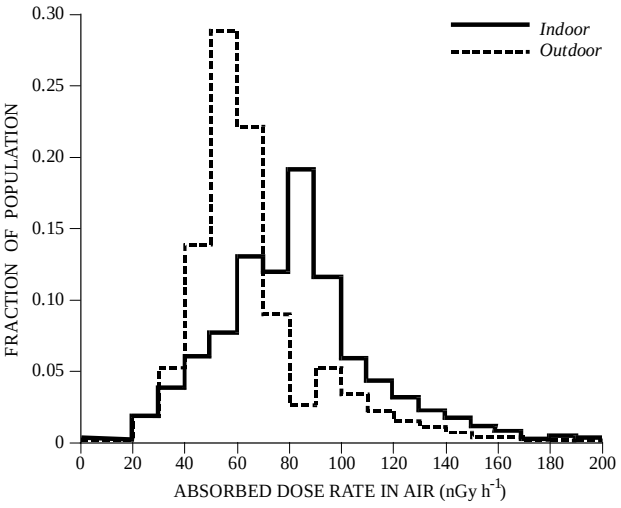

Figure VII. Comparison of indoor and outdoor exposure rates for the total population of nine European countries.

3. Effective dose

62. To estimate annual effective doses, account must be taken of (a) the conversion coefficient from absorbed dose in air to effective dose and (b) the indoor occupancy factor. The average numerical values of those parameters vary with the age of the population and the climate at the location considered. In the UNSCEAR 1993 Report [U3], the Committee used 0.7 Sv Gy^{-1} for the conversion coefficient from absorbed dose in air to effective dose received by adults and 0.8 for the indoor occupancy factor, i.e. the fraction of time spent indoors and outdoors is 0.8 and 0.2, respectively. These values are retained in the present analysis. From the data summarized in this Chapter, the components of the annual effective dose are determined as follows:

Indoors: 84 nGy h^{-1} × 8,760 h × 0.8 × 0.7 Sv Gy^{-1} = 0.41 mSv
Outdoors: 59 nGy h^{-1} × 8,760 h × 0.2 × 0.7 Sv Gy^{-1} = 0.07 mSv

The resulting worldwide average of the annual effective dose is 0.48 mSv, with the results for individual countries being generally within the 0.3–0.6 mSv range. For children and infants, the values are about 10% and 30% higher, in direct proportion to an increase in the value of the conversion coefficient from absorbed dose in air to effective dose.

B. INTERNAL EXPOSURES OTHER THAN RADON

63. Internal exposures arise from the intake of terrestrial radionuclides by inhalation and ingestion. Doses by inhalation result from the presence in air of dust particles containing radionuclides of the ^{238}U and ^{232}Th decay chains. The dominant component of inhalation exposure is the short-lived decay products of radon, which because of their significance are considered separately in Section II.C. Doses by ingestion are mainly due to ^{40}K and to the ^{238}U and ^{232}Th series radionuclides present in foods and drinking water.

64. The dose rate from ^{40}K can be determined directly and accurately from external measurements of its concentration in the body. The analysis of the content of uranium- and thorium-series radionuclides in the body requires more difficult chemical analyses of tissues, and fewer data are available. The analysis of the radionuclide contents of foods and water, along with bioassay data and a knowledge of the metabolic behaviour of the radionuclides, provides an alternative basis for dose estimation. The samples are more readily obtained, and they can reflect widely different locations. With these data, dose estimates for children as well as adults can be derived. The results of both approaches are presented in Section II.B.2.

1. Inhalation

65. Inhalation intake of natural radionuclides other than radon and its decay products makes only a minor contribution to internal exposure. Broadly representative breathing rates are listed in Table 13 for infants (1 year old), children (10 years old), and adults. Results of measurements of the concentrations of uranium- and thorium-series radionuclides in air are listed in Table 14. These radionuclides are present in air because of resuspended soil particles; the decay products of radon are present because of radon gas in air. A dust loading of 50 μg m^{-3} is generally assumed [U6, U7]. With ^{238}U and ^{232}Th concentrations in the soil of 25–50 Bq kg^{-1}, the concentrations in air would be expected to be 1–2 μBq m^{-3}, and this is generally what is observed.

66. It is important to note that the dust loading of air contains substances other than soil, including considerable proportions of organic matter and, especially in wintertime, fly ash from coal burning [K10]. The organic content is deficient in uranium compared to soil, but fly ash contains much higher concentrations of uranium. At coastal locations, concentrations of uranium in sea air may be an order of magnitude lower than in continental or industrialized areas [K11]. Somewhat higher concentrations were measured before 1980, as reported, for example, by Stevenson and Pan [S8]. The subsequent reductions may reflect different fuel supplies.

67. In the UNSCEAR 1993 Report [U3], representative values of the concentrations of terrestrial radionuclides in air were selected. As the database has changed very little, most of these values, as given in Table 14, are still considered valid. The highest concentration is for ^{210}Pb. The concentrations of the other radionuclides are lower by factors of 10, 500, or 1,000 (see Table 14).

2. Ingestion

68. Ingestion intake of natural radionuclides depends on the consumption rates of food and water and on the radionuclide concentrations. The reference food consumption profiles in Table 13 are derived from information on consumption rates adopted by the World Health Organization (WHO) [W1] and food balances compiled by the Food and Agriculture Organization of the United Nations (FAO) [F1]. The values are best interpreted as average values for adults. Consumption rates for children and infants are taken to be two thirds and one third, respectively, of these values, except for milk products, which are consumed in greater amounts by infants and children [C4]. The water intakes are based on reference water balance information from the International Commission on Radiological Protection (ICRP) [I4]. Although the tabulated values are in reasonable agreement with other assessments, there are substantial uncertainties implicit in their mode of derivation. Moreover, there are large deviations from this profile in various parts of the world, e.g. lower milk consumption in Asia and lower leafy vegetable consumption in Africa [W1].

69. Concentrations of naturally occurring radionuclides in foods vary widely because of the differing background levels, climate, and agricultural conditions that prevail. There are also differences in the types of local foods that may be included in the categories such as vegetables, fruits, or fish. In the UNSCEAR 1993 Report [U3], reference values were selected for the concentrations of uranium- and thorium-series radionuclides in foods. Obviously, these values must be derived from the most widely available and representative data possible. The database is summarized in Table 15.

70. It is difficult to select reference values from the wide ranges of concentrations reported for uranium- and thorium-series radionuclides in foods. An example may be made of ^{210}Po, which is present in relatively high concentrations in seafood. The importance of ^{210}Po to dietary intake has been

pointed out for countries such as Japan [Y1], the Marshall Islands [N2], Portugal [C1], and South Africa [H1]. A global review of ^{210}Po in marine food [A3] has suggested that representative concentrations are 2,400 mBq kg^{-1} in fish, 6,000 mBq kg^{-1} in crustaceans and 15,000 mBq kg^{-1} in molluscs. Consumption of fish and shellfish varies widely from country to country and between individuals in a single country. If representative consumption rates are 13 kg a^{-1} of fish and 1 kg a^{-1} each of molluscs and crustaceans, the intake of ^{210}Po with these foods would be 52 Bq a^{-1}. If there are processing or distribution delays for fish products between catch and consumption, the activity intake will be reduced owing to the radioactive decay of ^{210}Po. Statistics quoted by Aarkrog et al. [A3] indicate that 30% of seafood is eaten fresh, 30% frozen, 20% smoked, and 20% canned. For time delays of 0, 1, 2, and 12 months, respectively, the weighted mean time delay is 93 days, slightly less than one physical half-life of ^{210}Po. Application of the correction factor 0.6 suggests an annual intake of 31 Bq in seafood and a weighted concentra-tion of ^{210}Po in fish products of 2,100 mBq kg^{-1}. This result substantiates the reference value of 2,000 mBq kg^{-1} [U3].

71. Estimates of uranium- and thorium-series radionuclides in the total diet are presented in Table 16. They are determined from market-basket evaluations or from duplicate diet samplings. The values derived by multiplying the reference concentrations in foods and water and the intake amounts for adults are shown for comparison. The agreement with presently available data is reasonable.

72. The distributions of the annual intakes in various countries of uranium- and thorium-series radionuclides are shown in Figure VIII. Each point in the Figure represents the average value of the intake for a particular country. If only a range of values has been reported and listed in Table 16, the geometric mean of the extremes of the range has been taken as the representative value. The distributions are approxi-mately log-normal for each radionuclide and span an order of magnitude. Lead-210 and ^{210}Po have the highest concentra-tions and similar distributions, and ^{230}Th and ^{232}Th have the lowest concentrations and also similar distributions. Radium-226 and ^{238}U have intermediate concentrations. Because drinking water is important for the intake of uranium and radium radionuclides, it is necessary to ascertain that this source of ingestion intake is included in the dietary intake estimates.

73. There are a number of circumstances in which the concentrations of natural radionuclides in ingested food and water substantially exceed the reference concentrations or the more typical range of variation. Examples cited in previous UNSCEAR Reports include the Arctic food chain and the high levels of uranium-series radionuclides in well water. Since not all components of the diet are affected and because of common widespread distributions of foods of many different origins over larger regions, the doses to individuals in local populations are not usually so markedly elevated. The circumstances of such exposures should be better described and the data more systematically evaluated.

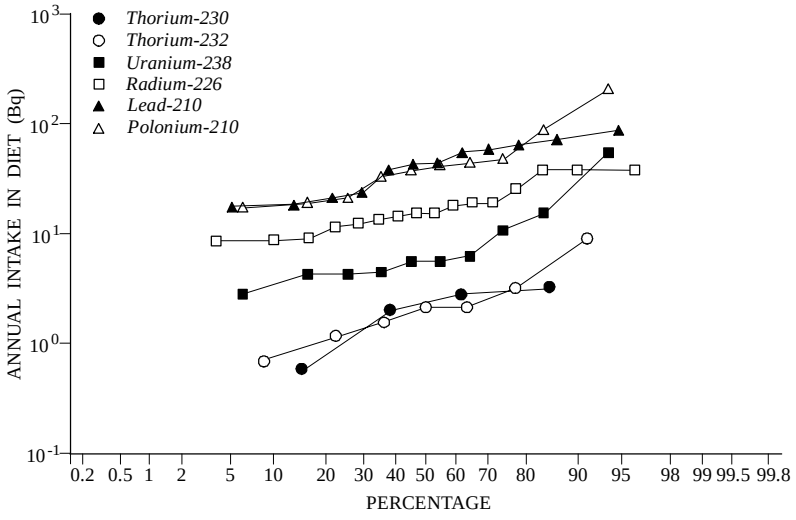

Figure VIII. Ranked distribution of annual intakes of uranium and thorium series radionuclides in diet.
Each point represents the average result of measurements made within a country.

3. Effective dose

74. The evaluation of the internal doses from inhalation is presented in Table 17. Revised dose coefficients taken from ICRP [I9] are used. The age-weighted annual effective dose is 6 μSv from inhalation of uranium- and thorium-series radionuclides in air, which may be compared to the 10 μSv derived in the UNSCEAR 1993 Report [U3].

75. Potassium is more or less uniformly distributed in the body following intake in foods, and its concentration in the body is under homeostatic control. For adults, the body content of potassium is about 0.18%, and for children, about 0.2%. With a natural abundance of 1.17 10^{-4} for ^{40}K [F6], a specific activity of 2.6 10^{8} Bq kg^{-1}, and a rounded dose conversion coefficient of 3 μSv a^{-1} per Bq kg^{-1} [N1], the annual equivalent doses in tissues from ^{40}K in the body are 165 and 185 μSv a^{-1} for adults and children, respectively. The same values are

appropriate for the effective doses, given the more or less uniform distribution of potassium within the body.

76. The evaluation of the internal doses from ingestion of uranium- and thorium-series radionuclides is presented in Table 18. The reference values of concentrations in foods are used with the consumption rates for infants, children, and adults. The age-weighted effective dose assumes a fractional population distribution of 0.05, 0.3, and 0.65, respectively, for infants, children, and adults. Some revisions have been made to the dose coefficients since the UNSCEAR 1993 Report [U3]. The revised values of the dose coefficients [I2] give generally higher estimates of effective dose for these radionuclides. Much of the dose is due to ^{210}Po, for which the gut uptake value recommended by ICRP increased from 0.1 to 0.5. Some of the reference concentrations of ^{210}Pb and ^{210}Po in foods (Table 15) have also been slightly revised. The age-weighted total value is 140 μSv, compared with 52 μSv derived in the UNSCEAR 1993 Report [U3].

77. The total effective dose from inhalation and ingestion of terrestrial radionuclides is 310 μSv, of which 170 μSv is from ^{40}K and 140 μSv is from the long-lived radionuclides in the uranium and thorium series. Essentially the same result is obtained for radionuclide concentrations in body tissues.

78. The Committee reviewed the concentrations of natural radionuclides in tissues in previous assessments, most recently in the UNSCEAR 1988 Report [U4]. Because of the low concentrations in tissues of uranium- and thorium-series radionuclides and variations with age and geographical location, the representative levels remain somewhat uncertain. As additional studies are published only infrequently, this situation is unlikely to change. The database is summarized in Table 19.

79. Uranium is retained in the body primarily in the skeleton. It has been shown that the concentrations are approximately similar in various types of bone (vertebrae, rib, femur) [H23]. Fisenne and Welford [F8] reported that, for residents of New York, concentrations of ^{238}U in vertebrae increased by a factor of 2 over the range 14–73 years and in lungs by a factor of 3 over the same age range. There were no such variations for liver and kidneys. Lianqing and Guiyun [L1] found no variation in concentrations of ^{238}U in bone with age for adult residents of Beijing, but the concentrations in bone of children were up to two times greater than the concentrations in adults. The wide range of concentrations in bone in samples from Beijing (94–2,600 mBq kg^{-1} in dry bone) illustrates the great variations encountered. The generally higher concentrations in Beijing are related to a high intake of ^{238}U in the diet and drinking water [L1].

80. An earlier estimate was that 70% of the body content of ^{238}U was in bone [J9, U6]. This would correspond to 500 mBq in the skeleton (assuming the reference concentration of ^{238}U in bone to be 100 mBq kg^{-1}) and 710 mBq in the body. The average concentration in soft tissues would then be 3 mBq kg^{-1}, although higher concentrations are measured in the lungs and kidneys.

81. Following intake by ingestion and inhalation, thorium is mainly deposited on bone surfaces and retained for long periods. Metabolic modelling assumes that 70% of the body content of thorium is retained in the skeleton [I5]. From the reference concentrations given in Table 19 and assuming the cortical bone mass to be 4 kg and the trabecular bone mass to be 1 kg, it may be estimated that the body burdens are 210 mBq of ^{230}Th and 70 mBq of ^{232}Th.

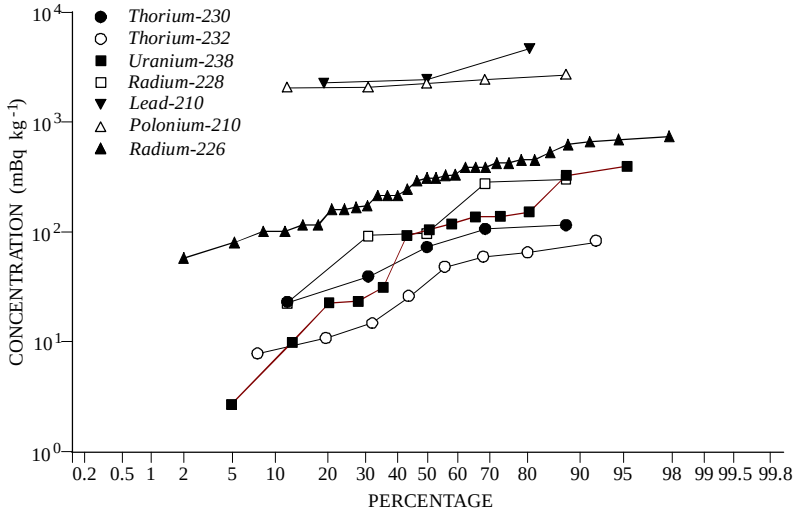

Figure IX. Ranked distribution of the concentrations of uranium and thorium series radionuclides in bone.
Each point represents the average result of measurements made within a country.

82. The distributions of uranium and thorium concentrations in bone in various countries are shown in Figure IX. The values are taken from Table 19. Because the distribution is log-normal within a country, the geometric mean is taken to be the most representative central value. If only a range of values has been reported, the geometric mean of the extremes is plotted in the Figure. The values for individual countries are also distributed approximately log-normally and extend over an order of magnitude, with the variation being caused primarily by differences in intake of the radionuclides in foods

and water. The distributions for ^{238}U and ^{230}Th in bone are similar; somewhat lower concentrations are reported for ^{232}Th. Based on available data, the reference concentrations of uranium and thorium radionuclides given in Table 19 have been revised. These data are limited and must be confirmed as representative for the countries. The concentrations of ^{238}U in soft tissues reported for the former Soviet Union, for example, appear to be abnormally high.

83. Data on ^{226}Ra, ^{210}Pb and ^{210}Po in tissues are also included in Table 19 (the ^{226}Ra data are in summary form). Radium is retained primarily in bone, and concentrations have been measured in many countries. In the UNSCEAR 1977 Report [U7], data from 16 countries were reported, which gave an arithmetic mean value of about 300 mBq kg^{-1} in dry bone. With the fraction of ^{226}Ra in the body distributed in soft tissues taken to be 17% [I3], the average concentration in soft tissues was inferred to be 4.8 mBq kg^{-1}. The population-weighted average of the same data gives somewhat lower values: 230 mBq kg^{-1} in bone and 3.6 mBq kg^{-1} in soft tissues.

84. On the basis of an extended compilation of data from 26 countries, Fisenne [F15] determined the median value of ^{226}Ra in bone from a cumulative population frequency plot to be 170 mBq kg^{-1} in bone. This value was quoted in the UNSCEAR 1982 Report [U6] and accepted as a reference value in the UNSCEAR 1988 and 1993 Reports [U3, U4]. From a further extended series of measurements in 31 countries that include over 60% of the world population, Fisenne [F16] more recently reported a median value of 260 mBq kg^{-1} in bone, inferred from a cumulative frequency plot. The population-weighted averages for these 26 and 31 countries are 230 and 310 mBq kg^{-1}, respectively. Several larger countries with relatively high concentrations in bone have been added to the extended list: Nigeria, 760; Russian Federation, 500; Brazil, 380; and China, 360 mBq kg^{-1}. A higher reference value for ^{226}Ra in dry bone in the range 200–300 mBq kg^{-1} is thus suggested.

85. The only recent data on ^{210}Pb and ^{210}Po concentrations in tissues are those from Japan [T13]. Lead accumulates in bone; by contrast, polonium is distributed mainly to soft tissues. Both would be present in the body in the absence of direct intake from decay of ^{226}Ra, but dietary intake is of most importance in establishing body contents. Early measurements showed the $^{210}Pb/^{210}Po$ concentration ratios to be 0.8 in bone, 0.5 in lungs, and generally 1 in other soft tissues [U7]. Some enhancement of ^{210}Po in liver and kidneys seems substantiated by the data in Table 19. The presence of ^{210}Pb and ^{210}Po in tobacco greatly increases the intake of these radionuclides by smokers. The measured ^{210}Po concentration in the lung parenchyma of smokers is about 3 times that of non-smokers [C32, H35].

86. The annual effective dose from the reference values of uranium–and thorium–series radionuclides in tissue was evaluated in the UNSCEAR 1988 Report [U4]. The estimate was adjusted with revised tissue weighting factors in the UNSCEAR 1993 Report [U3]. The result was 130 μSv. Some changes have been made in the reference concentrations in the present evaluation, and an adjusted value of 120 μSv is obtained. The main contributor to this dose is ^{210}Po. The details of this evaluation are presented in Table 20. This result is in close agreement with the estimate of 110 μSv derived from the dietary consumption of adults and the reference concentrations in foods and water (Table 18).

87. Further data from direct measurements of radionuclides in human tissues would be needed to establish more broadly based estimates of the annual effective dose from internal radionuclides. Studies involving measurements of both radionuclide intake and tissue contents in particular populations would be especially useful to better define the sources and variations in exposures and the magnitudes of the uncertainties in the estimated doses. However, because of the limited number of samples available and therefore the difficulties in determining representative concentrations of natural radionuclides in tissues, it may be necessary to put more reliance on the more widely based dietary intake data for dose estimation purposes.

C. RADON AND DECAY PRODUCTS

88. Radon and its short-lived decay products in the atmosphere are the most important contributors to human exposure from natural sources. While the health risks associated with high radon exposures in underground mines have been known for a long time, relatively little attention was paid to environmental radon exposures until the 1970s, when some scientists began to realize that indoor radon exposures could be quite high, in some cases comparable to the exposures experienced by many underground miners. Since then, the flood of information on radon continues unabated. Many of the more recent papers on the subject have appeared in the proceedings of international conferences at Salzburg (1991), Rimini (1993), Montreal (1995), Prague (1995), Fukuoka (1997), and Athens (1999) [C2, E8, H2, J1, K13, S65], and a valuable synthesis of European research on the subject has recently been published [E2]. All of this information is improving the understanding of the environmental processes that affect radon exposure, but there are still many problems associated with the accurate assessment of exposures and doses to individuals and populations.

89. It is well known that inhalation of the short-lived decay products of ^{222}Rn, and to a lesser extent the decay products of ^{220}Rn (thoron), and their subsequent deposition along the walls of the various airways of the bronchial tree provide the main pathway for radiation exposure of the lungs. This exposure is mostly produced by the alpha particles emitted by several of these radionuclides, although some beta particles and gamma radiation are also emitted. There is general agreement among scientists that it is the alpha particle irradiation of the secretory and basal cells of the upper airways that is responsible for the lung cancer risk seen in miners, although there remains some uncertainty as to exactly which cells are most important for the subsequent induction of lung cancer. It is this situation that is central to the problem of dose assessment. The key

point is that alpha particles emitted into the walls of the airways have a short range, tens of micrometers, and there are large variations in the density of ionizations and excitations along and near the tracks. Thus, the damage to the critical target cells of the respiratory tract depends in a sensitive manner on the source/target geometry. It follows that the dose that is relevant to risk depends critically on those environmental factors that affect the probability that the radon decay products are deposited near the critical target cells after inhalation, as well as on the overall inhalation rate of these decay products. In the following paragraphs, the current concept of radon exposure is described and information on how various environmental factors influence such exposure is summarized, along with available data on exposure levels outdoors and indoors. Absorbed doses to the critical cells and effective doses are then determined by applying the exposure-to-dose conversion factors.

90. The radioactive properties of ^{222}Rn and ^{220}Rn and their respective short-lived decay products are given in Table 3. The various half-lives of the radionuclides are very important in determining the relative contributions of the two series to bronchial dose. The half-life of ^{222}Rn is 3.824 d. It has four short-lived decay products: ^{218}Po (3.05 min), ^{214}Pb (26.8 min), ^{214}Bi (19.9 min), and ^{214}Po (164 μs). Both polonium isotopes are alpha-emitters. The relatively short half-life of ^{220}Rn (55.6 s) means that it does not have much time to travel from its production site to the immediate environment of human beings. The relatively long half-life of one of its decay products, ^{212}Pb (10.6 h), allows this isotope time to deposit on surfaces or migrate away from its source before producing the important alpha-emitter ^{212}Bi (60.6 min). The relative concentrations of the various radionuclides in the two series are also strongly affected by dynamic processes, including the attachment of the decay products to aerosol particles and their subsequent deposition on room surfaces or the ground as well as air movement in general. The fraction of radon progeny in an ultrafine mode (0.5–2 nm), not attached to ambient aerosol particles, is known as the unattached fraction [H5, T16].

91. The evaluation of exposure to radon and the decay products must thus take account of the actual activity concentrations of the various alpha-emitting radionuclides in the two series in the air that is breathed. This consideration, as well as the fact that it is the total alpha particle energy yet to be released by, or following, the decay of inhaled radionuclides that is important in determining dose, has led to the definition of radon exposure rate in terms of potential alpha energy concentration (PAEC) with unit of J m^{-3} or of WL (working level). This quantity can be readily calculated once the activities of the individual radionuclides have been determined from measurement. In most cases, the individual activities are not directly measured, so that the exposure rate must be indirectly determined using assumptions made on concentration ratios, i.e. equilibrium factors, leading to the determination of the equilibrium equivalent concentration. The essential point here is that environmental factors that influence concentration ratios in each of the radioactive series are of great significance for both exposure and dose assessments.

1. Sources of radon

(a) Entry into the atmosphere

92. Radon-222 and ^{220}Rn are the gaseous radioactive products of the decay of the radium isotopes ^{226}Ra and ^{224}Ra, which are present in all terrestrial materials. Some of the atoms of these radon isotopes are released from the solid matrix of the material by recoil when the radium decays. For a radon atom to escape from the mineral grain into the pore space, the decay must occur within the recoil distance of the grain surface. The range of recoil distance for ^{222}Rn is 20–70 nm in common minerals, 100 nm in water, and 63 μm in air [T2]. Radon atoms entering the pore space are then transported by diffusion and advection through this space until they in turn decay or are released into the atmosphere (exhalation). The processes of radon emanation and transport, particularly in the soil, have been reviewed in several classic papers by Tanner [T1, T2]. New studies have focused on the effect of moisture, the dynamics of release or recoil from minerals, radon behaviour in soils as well as on aspects of geology and climate [G22, S50, S59, S60, W9]. Radon generation and transport in porous materials involve solid, liquid, and gas phases in the processes of emanation, diffusion, advection, absorption in the liquid phase, and adsorption in the solid phase. Most aspects of these processes have been characterized individually; however, practical applications require a unified theoretical framework that considers the processes simultaneously [N6, R11].

93. The fraction of radon atoms released into rock or soil pore space from a radium-bearing grain is called the emanation coefficient, the emanation factor or the emanating power. Factors affecting the emanation coefficient were reviewed by Schumann and Gundersen [S50]. Typical emanation coefficients for rocks and soils range from 0.05 to 0.7 [N19]. Grain size and shape are two important factors that control the emanation of radon in soil. They determine how much radium is near enough the grain surface to allow radon to escape into pore spaces. Generally the radon emanation factor is inversely proportional to grain size. The presence of radium in increased concentrations in surface coatings of the grains increases the emanating power relative to that in which radium is uniformly distributed throughout the grains. The sorption or co-precipitation of radionuclides with metal oxides [G18] or organic compounds [G17] in grain coatings is one of the most important processes enhancing the radon emanation coefficient. A study of granitic esker sand showed a high degree of radioactive disequilibrium between ^{226}Ra and ^{238}U, caused by ^{226}Ra adsorbed on the surface of mineral particles [E5]. Microscopic fractures and fissures, called nanopores, and pits or openings caused by previous radioactive decays provide additional pathways for radon release. Particularly in sand-sized and larger grains, nanopores can increase the specific surface area of the grain, enhancing emanation by one or two orders of magnitude.

94. Soil moisture plays an important role in the emanation of radon and its diffusion in soil, for several reasons. Soil moisture, in the form of a thin film of water surrounding soil

grains, directly affects radon emanation by capturing the radon recoils from the solid matrix. These captures increase the likelihood that radon atoms will remain in the pore space instead of crossing the pores and imbedding themselves in adjacent soil grains. Both theoretical estimates [R11] and laboratory tests show that adsorption on soil grains decreases rapidly with increasing water content, becoming insignificant for water contents greater than about 0.3–0.4 of saturation. Decreased adsorption increases the emanation factor at low water contents. Once radon enters the pore space, its partition between the gas and liquid phases depends on the relative volume of water in the pore space and on temperature. The solubility of radon in water decreases with temperature. The partition coefficient of radon between water and gas, the Ostwald coefficient K_T, gives the ratio of concentrations of radon in water and in air [A4, C28, W9]. The value of K_T varies from 0.53 at 0°C to 0.23 at 25°C in water and is typically 0.30 at 15°C. Both partitioning and increased emanation cause the concentration of radon in the air-filled pores to be higher under moist conditions than under dry conditions [A4, W9].

95. The concentration of radon in soil gas, C_{Rn}, in the absence of radon transport is as follows [N19, W9]:

$$C_{Rn} = C_{Ra}\, f\, \rho_s\, \varepsilon^{-1} (1-\varepsilon) (m [K_T - 1] + 1)^{-1} \qquad (1)$$

where C_{Ra} is the concentration of radium in soil (Bq kg^{-1}), f is the emanation factor, ρ_s is the density of the soil grains (2700 kg m^{-3}), ε is the total porosity, including both water and air phases, m is the fraction of the porosity that is water-filled (also called the fraction of saturation), and K_T is the partition coefficient for radon between the water and air phases. For dry soil, m is zero and the last term on the right side of the equation can be omitted. A warm, moist soil (25°C, K_T = 0.23, m = 0.95) with typical soil parameters (C_{Ra} = 30 Bq kg^{-1}, f = 0.2, ε = 0.25) will have a concentration of radon in pore air of 78 kBq m^{-3}, which is 3.7 times higher than for the same soil under cold and dry conditions (0°C, K_T = 0.53, m = 0.05, C_{Rn} = 21 kBq m^{-3}) [W9].

96. Radon concentrations in soil within a few meters of the surface of the ground are clearly important in determining radon rates of entry into pore spaces and subsequently into the atmosphere. They depend on the distribution and concentrations of the parent radium radionuclides in the bedrock and overburden and on the permeability of the soil. Certain generalizations can be made about the radium concentrations in bedrocks of various types, but there are very large ranges within each type. In general, granites have relatively high radium contents, sedimentary and metamorphic rocks intermediate contents, and basalts and most limestones low contents, although there are many striking exceptions to this rule. Soils are similarly variable in their radium content, and generalizations here are even more difficult. This is due in part to the often complex relationship between the bedrock and its overburden, especially in those higher latitude regions that were subject in the past to glaciation. Radium transfers more readily to vegetation than the parent uranium radionuclides, and the emanation from soil organic matter is more effective than from soil minerals. The effective permeabilities of bedrocks and soils are also highly variable, being related to degree of weathering, porosity, moisture content, and the presence of cracks or fissures. This was demonstrated by Schumann and Gundersen [S50] for different soils and climates in the United States. The regional differences are probably caused by climate-controlled differences in soil weathering processes.

97. The key soil-related parameters characterizing radon transport are the radon diffusion coefficient and the soil-air permeability. The diffusion coefficient relates the gradient of the radon concentration in air-filled pores to the flux. It can be determined in many ways, which may cause confusion. The pore diffusion coefficient D_e is also called the "interstitial" or "effective" diffusion coefficient. It relates the gradient of the radon concentration in air-filled pores to the flux density across the air-filled pore area. The "bulk" diffusion coefficient relates the same gradient to the flux density across the geometric (bulk) area. The pore volume is divided into air-filled and water-filled parts. An approximate relationship states that the bulk diffusion coefficient D is equal to εD_e, where ε is the porosity of the soil. Since the radon concentrations in the air-filled and water-filled parts are not the same, the parameter ε must be replaced by the expression $\varepsilon_a + K_T\, \varepsilon_w$, which takes into account the partitioning [A4, N19, R11].

98. Simple models are needed to determine the key parameters of the diffusion coefficient and the soil-air permeability for radon transport calculations. Rogers and Nielson presented a brief review of such expressions [R12]. They also introduced an updated correlation for the effective diffusion coefficient, which was based on more than a thousand diffusion measurements. The experimental pattern of the effective diffusion coefficient D_e as a function of the volume fraction of water saturation is given in Figure X. At low water content, D_e is a little affected by the water content. At high water content, the pores become blocked by water and the diffusion decreases. Typical porosity values for soil materials are 0.01–0.5, with 0.25 representing an average value [U3]. Typical water saturation fractions are 0.1–0.3 for sand and 0.3–0.95 for loam, silty clay, or clay [N7]. The range of D_e in soil is typically 10^{-7}–10^{-5} m^2 s^{-1}. For soil with a fractional water saturation of 0.2 and a porosity of 0.25, the data in Figure X yield an effective diffusion constant of 2 10^{-6} m^2 s^{-1}, which is used as the representative value for soil beneath the reference house (Table 21). In the case of a dry soil (with a total porosity ε of 0.25), the corresponding bulk diffusion coefficient of 5 10^{-7} m^2 s^{-1} is the product of a soil porosity of 0.25 and a D_e of 2 10^{-6} m^2 s^{-1}. This value of the bulk diffusion coefficient corresponds to the representative value given in the UNSCEAR 1988 and 1993 Reports [U3, U4]. If the partitioning has been taken into account, e.g. at a fraction of saturation m of 0.2 (ε = 0.25, ε_a = 0.20 and ε_w = 0.05) and at a temperature of 15°C (K_T = 0.3), the corresponding bulk diffusion coefficient is lower, 4.3 10^{-7} m^2 s^{-1}.

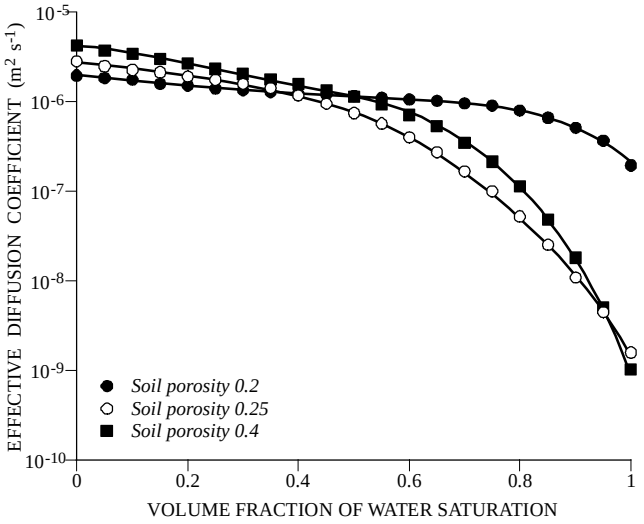

Figure X. Experimental pattern of the effective diffusion coefficient of radon for soil of three different porosities as a function of the fraction of saturation [R12].

99. The main mechanism for the entry of radon into the atmosphere is molecular diffusion. An expression to estimate the diffusive entry rate of radon into the atmosphere was considered in the UNSCEAR 1988 and 1993 Reports [U3, U4]. For a porous mass of homogeneous material semi-infinite in extent, the flux density of radon at the surface of dry soil J_D (Bq m^{-2} s^{-1}) is given by the expression

$$J_D = C_{Ra} \lambda_{Rn} f \rho_s (1-\varepsilon) L \quad (2)$$

where C_{Ra} is the activity concentration of ^{226}Ra in earth material (Bq kg^{-1}), λ_{Rn} is the decay constant of ^{222}Rn ($2.1\ 10^{-6}$ s^{-1}), f is the emanation fraction for earth material, ρ_s is the soil grain density (2700 kg m^{-3}), and ε is the porosity of dry earth material. The diffusion length, L, is equal to $(D_e/\lambda_{Rn})^{½}$. With representative values of these parameters (C_{Ra} = 40 Bq kg^{-1}, f = 0.2, D_e = $2\ 10^{-6}$ m^2 s^{-1}, ε = 0.25), J_D is 0.033 Bq m^{-2} s^{-1}. Equation (2) is valid only for dry soil. The presence of water in soil alters the transport conditions, resulting in a modified equation for J_D. In addition, moisture affects the emanation coefficient and the diffusion coefficient. The estimate of J_D, 0.033 Bq m^{-2} s^{-1}, is in approximate concordance with measured values; however, it is higher than the estimated mean worldwide flux of ^{222}Rn of 0.016 Bq m^{-2} s^{-1} [W8].

100. Although diffusive entry of radon into the outdoor atmosphere usually dominates, there is also some advection caused by wind and changes in barometric pressure. Measurements of exhalation rates of radon from soil show a variability that reflects the variability of radon concentrations in near-surface pore spaces. Concentrations of ^{222}Rn in soil gas vary over many orders of magnitude from place to place and show significant time variations at any given site. Data have shown that there were prominent increases in radon concentrations in outdoor air and in ground water just before the large earthquake at Kobe, Japan, in 1995 [I11, Y3].

101. Under normal circumstances, thoron concentrations in soil gas would be roughly comparable to or perhaps somewhat less than the ^{222}Rn concentrations because of the generally similar production rates in rocks and soils and their similar behaviour in the ground. This has been observed at two locations in New Jersey, United States [H3]. On the other hand, high thoron entry rates from the ground are rarely encountered. Whereas fractures in the ground and/or bedrock allow ^{222}Rn to be pulled to the surface from substantial depths (and volumes), the time frame may be such that most of the thoron present at these depths decays before reaching the surface.

(b) Entry into buildings

102. Knowledge of the factors that influence ^{222}Rn entry rates into structures has considerably improved in recent years as a result of investigations of the processes involved and evaluations of simplified model houses [G1, H4, N16, N19]. In the UNSCEAR 1988 and 1993 Reports [U3, U4], a model masonry building with a volume of 250 m^3, surface area of 450 m^2, and an air exchange rate of 1 h^{-1} was described and calculations carried out to illustrate the effects of the several mechanisms of radon entry, including diffusion and advection from the ground and the building materials, the entry of outdoor air, and ^{222}Rn released from water and natural gas. In the following paragraphs the contributions of these entry mechanisms are reevaluated. The representative soil and house parameters used in the estimation are given in Table 21.

103. Many studies have shown that when high rates of radon entry into buildings are found, advection is usually the main factor [E2, M4]. This advection is driven by the pressure differential between the building shell and the ground around the foundation, produced by the higher temperatures within the shell (the "stack" effect), mechanical ventilation, and to some degree also by wind blowing on the building. The effectiveness of this pressure differential in pulling in radon-laden soil gas through the foundation is critically dependent on the effective permeabilities of both the building foundation and the adjacent earth. Wind can also cause decreases in radon entry concentrations by its flushing effect on radon in soil surrounding the house [R8]. Under certain conditions, atmospheric pressure fluctuations can also represent an important mechanism of radon entry [R13, R14]. Because of differences in the pressure differentials and permeabilities, the advection contribution varies greatly from structure to structure, at least in temperate and cold climates. For non-masonry buildings of similar dimensions in a tropical climate, account must be taken of the usual characteristics and conditions of board floors, calm air, balanced temperatures, and high ventilation (2 h^{-1}). The most important contributions to indoor radon in this case come from outside air and diffusion from the ground, but the total value is not much changed.

104. The effect of anomalous subterranean air flows on indoor radon concentrations has been observed in the United

States in hilly karst terrain [G14, R22] and in Finland on eskers [A5]. Eskers are long and narrow steep-sided ridges formed by glacial streams. In the United States, subterranean networks of cavities and fissures were observed to facilitate advective transport of radon-bearing air. In eskers the coarse sand facilitates underground air flows. In both cases differences between underground and outside air temperatures and the accompanying differences in air density cause subterranean air to move between the upper and lower parts of the area. Wind may also strongly affect the soil air and indoor radon concentrations in these areas. These flows amplify indoor radon levels in winter or summer, depending on the location of the house. Air flows due to thermal differences and seasonal patterns of radon concentrations, which are comparable with the observations described above, have been observed in caves and in mining regions close to the tunnels and air shafts [C27, L17, S39].

105. Modelling studies have helped in understanding the relevance of factors that influence ^{222}Rn entry rates into structures. The modelling results were reviewed by Gadgil [G1]. The main entry route into the model house is the gap between the foundation wall and the floor slab of concrete. The first analytical studies demonstrated the dominant effect of soil permeability; they also showed that once the gap width exceeds 0.5 mm, it no longer markedly increases the entry rate [M32, N8]. In later, mainly numerical model studies, the effect of a subfloor gravel layer, backfill, entry into slab-on-grade houses, and alternative entry routes were modelled [A4, L4, N6, R15, R16]. The gravel layer below the floor slab greatly increases the radon entry rate. Typically, when the ratio of gravel to soil permeability is over 100 and the soil permeability is less than 10^{-9} m^2, the aggregate layer increases the radon entry by a factor of 3–5 [A4, R15].

106. Permeability strongly affects the convective entry of radon into houses. The range of soil air permeability values is very broad, more than eight orders of magnitude, from less than 10^{-16} m^2 for homogeneous clay to more than 10^{-8} m^2 for clean gravel. In a house with a slab-on-grade, the gap between the floor slab and the foundation wall is the most important entry route for radon-bearing soil air. If the slab is otherwise radon-tight, high radon entry rates can only occur by means of advection, and the diffusive entry rate is of minor importance. For moderate permeabilities ($k > 10^{-12}$ m^2), the entry rate is proportional to the permeability and the pressure difference across the gap. The effect of soil permeability, calculated for a model house, is illustrated in Figure XI [R15]. Of great importance is the presence of cracks or fractures of any kind and of any scale in the solid matrix of the material. These magnify the effects of pressure and temperature differentials on the convective transport of radon. Fractures in bedrock formations, cracks in the soil, and similar inhomogeneities in the materials of the foundation of a structure have been identified as direct causes of high radon entry rates into many structures exhibiting high indoor radon concentrations [E2, K14, S3].

107. To estimate the diffusive entry rate from building materials, the flux density from one side of a building element, such as wall and floor, must be known. This is given by the following expression, presented in the UNSCEAR 1988 Report [U4]:

$$J_D = C_{Ra}\,\lambda_{Rn}\,f\,\rho\,L\,\tanh(d/L) \qquad (3)$$

where L is the diffusion length in concrete, given in equation (2), and d is the half-thickness of the slab. The equation is similar to that related to soil [equation (2)], the only difference being the introduction of the hyperbolic term. The parameters of wall materials given in Table 21 and a wall half-thickness of 0.1 m yield an estimate of 0.18 m for the diffusion length in concrete, the corresponding radon flux J_D being 0.0016 Bq m^{-2} s^{-1}. For a floor slab with a half-thickness of 0.05 m and values given in Table 21, the corresponding diffusion length and radon flux are 0.22 m and 0.0008 Bq m^{-2} s^{-1}. Because the diffusion lengths are greater than the half-thickness of the wall and floor, most of the free radon will be exhaled from the structures. Consequently, the thickness of the structure is a dominant factor affecting the radon flux. These flux densities estimated for building materials are about an order of magnitude less than the flux density from the semi-infinitive soil given above.

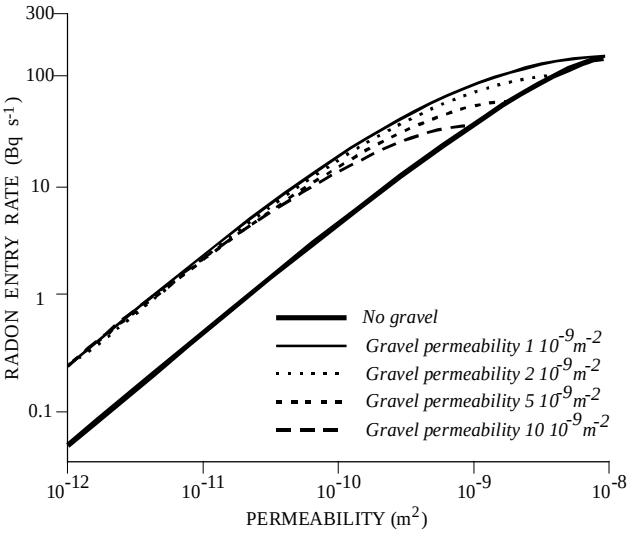

Figure XI. Advective radon entry rates into a typical basement [R15]. *Assumes slab-to-wall gap of 3 mm, deep soil radon concentration of 37 kBq m^{-3}, gravel layer beneath basement slab of thickness of 15 cm and basement pressure of –5 Pa with respect to the atmosphere.*

108. The rate of radon entry from the building elements in the reference house, U (Bq m^{-3} h^{-1}), is given by the expression

$$U = 3.6\,10^3\,S_B\,J_D\,/\,V \qquad (4)$$

where S_B is the surface areas of the walls, J_D is the flux density, and V is the volume of the house (m^3). The surface area of radon-emitting walls in the reference house is estimated to be approximately 450 m^2. The resulting value of U is about 10 Bq m^{-3} h^{-1}. Similarly, the entry rate from

a floor slab with a radon flux density of 0.0008 Bq m^{-2} s^{-1} and a surface area of 100 m^2 is 1.2 Bq m^{-3} h^{-1}. With an air exchange rate of 1 h^{-1}, the corresponding indoor radon concentrations in the reference house attributable to the materials of which the walls and floor slab are built are about 10 and 1 Bq m^{-3}.

109. Radon flux from concrete samples has been observed to vary over two orders of magnitude [S40, U3]. This is caused by differences in the ^{226}Ra content of the material, its porosity, density, and emanation fraction. Generally, radon diffusion from the soil through the concrete has been ignored; however, recent measurements from the United States show that radon diffusion through concrete can be a significant mechanism for radon entry into dwellings [R17]. Basically, this is because the quality of concrete in floor slabs is not as high as that of industrial concretes. The porosities are higher, resulting in higher diffusion constants. The measured effective diffusion coefficients in the extensive study in the United States ranged from 2 10^{-8} to 5 10^{-7} m^2 s^{-1}. These values are consistent with previous values in the literature; the upper limit of the range is extended by a factor of about 5. The geometric mean of 1.4 10^{-7} m^2 s^{-1} is sufficiently high to permit radon diffusion to be a significant mechanism for indoor radon entry under common long-term indoor pressures. The results indicate that the diffusion constant is also related to the porosity. The porosity corresponding to the geometric mean diffusion constant was approximately 0.20. When radon entry into the reference house presented in Table 21 was estimated, 1 10^{-7} m^2 s^{-1} was used for the effective diffusion coefficient of the floor slab. The corresponding estimate of the effective diffusion coefficient, 7 10^{-8} m^2 s^{-1}, presented in the UNSCEAR 1993 Report [U3], has been used for wall materials.

110. For a slab lying on the ground, the radon flux transmitted by the slab can be estimated using an empirical formula, e.g. [U4]. With the parameter values of Table 21, an estimate of 0.0071 Bq m^{-2} s^{-1} is obtained. This estimate is higher by a factor of 6 than the estimate presented in the UNSCEAR 1988 Report [U4], 0.0012 Bq m^{-2} s^{-1}, owing to differences in slab thicknesses, diffusion lengths, and radium concentrations in the soil. With a floor area of 100 m^2 and a flux density, J_T, of 0.007 Bq m^{-2} s^{-1} inserted into equation (4), the radon entry rate for the reference house is estimated to be 10 Bq m^{-3} h^{-1} (Table 22). This result is ten times higher than the radon flux from the slab and is comparable to the flux from walls of the reference house. This yields further an indoor radon concentration of 10 Bq m^{-3} when the air exchange rate is 1 h^{-1}. A comparison estimate is available from Figure XII [A4], which illustrates the entry rate through both the slab and the perimeter gap, including the diffusive and advective components. The parameters used in Figure XII were approximately those used for the reference house, Table 21. The diffusive entry through the slab can be estimated from the entry rate calculated for a permeability of 10^{-13} m^2. In this case, the diffusive entry predominates, and advection through the slab makes a negligible contribution. Figure XII yields an estimate of 0.97 Bq s^{-1}, or 0.0097 Bq m^{-2} s^{-1}, from the slab, which is consistent with the estimate above of 0.007 Bq m^{-2} s^{-1}, when the contribution of the diffusive entry rate from slab material of about 0.002 Bq m^{-2} s^{-1}, included in the estimate in Figure XII, is subtracted. In practice, the cover materials to some extent decrease the radon flux from the floor. In basement houses, diffusion of radon through concrete block walls may be a significant source of indoor radon [L21].

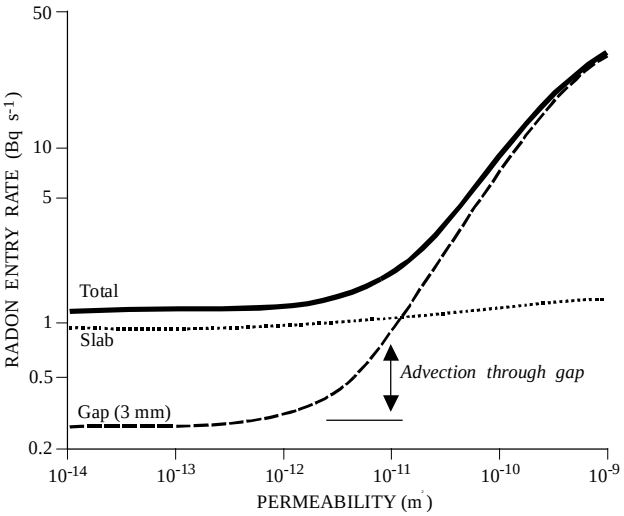

Figure XII. Radon entry rates for model masonry house [A4].

111. The diffusive entry rate through the gap between the floor slab and the foundation wall is next considered. Recent studies [A4, L4, N6, R15] provide improved data from models where diffusive transport is coupled with advective flow. Generally, the increased advective flow through the gaps of the floor slab decreases the relative contribution of diffusion. The upper limit of the diffusive entry rate through the 3 mm perimeter gap can be estimated roughly using the entry rate at the permeability of 10^{-13} m^2 s^{-1} (Figure XII). For this permeability, diffusive entry is the dominant entry mechanism. The estimated volumetric entry rate is 4 Bq m^{-3} h^{-1}. This estimate represents the upper limit for the diffusive entry rate through the gap and has been used as the representative entry rate for the reference masonry house (Table 22).

112. In the published modelling studies, the estimates of the soil-air leakage rate for a house with a basement and a basement wall-floor gap length of 40 m (floor slab of 100 m^2) on soil with permeability of 10^{-10} m^2 are in the range 0.8–2 m^3 h^{-1} [M32, R15]. In a one-floor house with slab-on-grade and a pressure difference of 1 Pa, the corresponding estimate would be 0.2–0.5 m^3 h^{-1}. When a flow rate of 0.2 m^3 h^{-1} and a leakage air concentration of 25,000 Bq m^{-3} are applied to the reference house of Table 21, the advective radon entry rate is 20 Bq m^{-3} h^{-1}. The leakage air concentration is 40% of the deep-soil radon concentration for the reference house. The pressure difference of 1 Pa represents an indoor-outdoor temperature difference of 20°C in a house with slab-on-grade and a natural ventilation system. The advective entry rate of 20 Bq m^{-3} h^{-1} represents a permeability of approximately 2 10^{-11} m^2. This estimate has been used as the representative value for the reference house (Table 22). In the absence of the

gravel layer the permeability would have to be higher by a factor of 2 to yield the same entry rate.

113. The estimates of radon entry into a reference masonry house derived in the preceding paragraphs are summarized in Table 22. Diffusive and advective radon entry each contribute about 40%, and the outdoor air contributes about 20%. The numerical estimates for the various contributions are subject to uncertainties because of the assumptions made. However, the results are roughly consistent with measurements made in actual buildings [H4]. The radon concentration of the reference house is approximately equal to the worldwide average indoor radon concentration. More specific comparisons are made in Table 23 for typical houses in Finland [A1], where the radon concentrations indoors are higher and the air exchange rates are lower than assumed for the reference house. The relative contribution of diffusion sources is lower when the main construction material is wood.

114. Radon dissolved in water may enter indoor air through de-emanation when the water is used. The water supply contribution depends on the concentration of radon in the water used for showering, laundry, etc., and can sometimes be important. The concentrations of radon in water may range over several orders of magnitude, generally being highest in well water, intermediate in ground water, and lowest in surface water. Reference values selected in the UNSCEAR 1993 Report [U3] were 100, 10, and 1 kBq m^{-3} and reference usage was 10%, 30%, and 60%, respectively, for water from the three sources. The ratio of concentrations in air and in water was taken to be 10^{-4} [U3]. This value was also recommended in a national review in the United States of experimental and model study results [N10]. Thus, an average concentration of radon in water of 10 kBq m^{-3} implies a contribution of 1 Bq m^{-3} to radon in air; for an air exchange rate of 1 h^{-1}, the radon entry rate is 1 Bq m^{-3} h^{-1} for the reference house (Table 22).

115. Further evaluation of water as a source of radon for indoor air (public water supplies were measured in 100 major cities of China) confirms these results. The range of radon concentrations in water was 0.04–100 kBq m^{-3}, with an average value of 8 kBq m^{-3} [R9]. Measurements of the air-water concentration ratio did, however, show somewhat higher values, 2–70 10^{-4} on average, in separate studies [R9]. An analysis of all the existing published data giving estimates of the transfer coefficient of radon from water to indoor air derived an average value of 1 10^{-4} [N10].

116. The results of analysing radon entry rates for the reference house suggest at least the relative contributions of the processes involved. The main practical result of such modelling studies has been to identify strategies to mitigate the high radon entry rates through the foundation that are usually the cause of high radon exposures [A11, C25, H19, W4]. These studies have also revealed how complex the situation is with respect to predicting entry rates for individual houses or explaining them when they are measured. Considering all of the factors mentioned above, and especially the design and quality of construction of an individual structure, the factors that determine the entry rate are many, varied, and very site-specific. Successful mitigation strategies, such as identifying and sealing a limited number of entry pathways or effectively ventilating the soil immediately adjacent to the foundation, tend to work because radon entry into many structures can be fairly readily prevented, or at least substantially reduced, by redirecting and re-channelling air transport away from building interiors. Radon concentrations are typically reduced by about 30%. Other techniques aim at reducing the building/ground pressure differential that drives the advection; the radon concentrations are then typically reduced by 80%–99%. Improvements in ventilation systems normally change radon concentrations by less than 50%.

117. The processes that may allow thoron to accumulate in indoor air are difficult to assess. Because of thoron's short half-life, it was once thought that the only mechanisms for significant thoron entry would be infiltration of outdoor air and diffusion from building materials. But recent investigations have shown that entry through the foundation can also be important [L3, S2]. There is an absence of detailed studies in a sufficiently large sample of buildings to make wide generalizations. However, given the comparable concentrations of ^{222}Rn and thoron usually found in outdoor air, soil gas, and building material pore spaces, it is not unexpected that indoor air concentrations of the two gases (ground floor level only) are often roughly comparable.

118. Many of the studies of ^{222}Rn and thoron source terms have dealt with single-family houses, with or without basements and crawl spaces. There is less information on multi-storey buildings, such as apartment houses and office buildings. The expectation that ground sources would be less important for spaces well above the ground has generally been supported by lower measured ^{222}Rn and thoron concentrations in higher storeys [S4], but the ground source contribution depends on air circulation patterns within the building that are both time- and building-dependent.

119. Considerable research has been carried out in recent years to develop methods for defining areas where there is an increased probability of finding buildings with high radon entry rates and indoor air concentrations. A number of models have been developed based on bedrock geology and soil characteristics that have met with only limited success, undoubtedly because of the complications indicated in the preceding paragraphs. Recent efforts in Finland [V3], Japan [F18], Sweden [A14], the United Kingdom [M1], and the United States [G2, P2] have shown that models that incorporate measured radon and radiation levels as well as relevant geological and geophysical parameters are likely to be the most effective.

2. Concentrations in air

(a) Outdoors

120. Concentrations of radon in the outdoor environment are affected not only by the magnitude of the exhalation rates in the general area but also by atmospheric mixing phenomena.

Solar heating during the daytime tends to induce some turbulence, so that radon is more readily transported upwards and away from the ground. At night and in the early morning hours, atmospheric (temperature) inversion conditions are often found, which tend to trap the radon closer to the ground. This means outdoor radon concentrations can vary diurnally by a factor of as much as ten. There are also seasonal variations related to the effects of precipitation or to changes in prevailing winds [B23]. These effects must be taken into account when interpreting the available measurements, many of which are daytime samples.

121. Recent results of radon measurements outdoors tend to confirm the estimates of typical outdoor ^{222}Rn and ^{220}Rn concentrations made in the UNSCEAR 1993 Report of 10 Bq m^{-3} for each [I14]. There is, however, a wide range of long-term average concentrations of ^{222}Rn, from approximately 1 to more than 100 Bq m^{-3}, with the former perhaps typical of isolated small islands or coastal regions and the latter typical of sites with high radon exhalation over large surrounding areas. Although data are sparse for thoron, considerable variability from place to place would be expected because of thoron's short half-life, which means that the effective surface source, about 0.1 km^2 [S4], is much smaller than that for ^{222}Rn, emphasizing the effect of local variations in exhalation rate. Even more important is the fact that thoron's short half-life results in a very steep vertical gradient in its atmospheric concentration at any location. A few measurements show that concentrations a few centimeters above the ground surface and concentrations at a height of 1 m vary by a factor of about 10 [D2, I10, N18]. This gradient would be expected to vary considerably with atmospheric conditions. Thus, pronounced time variations would be expected at any height above the ground at any location. This has obvious implications for estimating thoron exposure outdoors and the outdoor air source term for indoor thoron.

122. Direct measurement of the concentrations of all short-lived decay products of ^{222}Rn and ^{220}Rn are difficult and limited. They are estimated from considerations of equilibrium (or disequilibrium) between these nuclides and their respective decay products. An equilibrium factor F is defined that permits the exposure to be estimated in terms of the potential alpha energy concentration (PAEC) from the measurements of radon gas concentration. This equilibrium factor is defined as the ratio of the actual PAEC to the PAEC that would prevail if all the decay products in each series were in equilibrium with the parent radon. However, it is simpler to evaluate this factor in terms of an equilibrium equivalent radon concentration, C_{eq}, in the following manner:

$$F = C_{eq}/C_{rn}$$

$$C_{eq} = 0.105\ C_1 + 0.515\ C_2 + 0.380\ C_3 \qquad (^{222}\text{Rn series})$$
$$C_{eq} = 0.913\ C_1 + 0.087\ C_2 \qquad (^{220}\text{Rn series})$$

where the symbols C_1, C_2, and C_3 are the activity concentrations of the decay progeny, namely ^{218}Po, ^{214}Pb, and ^{214}Bi, respectively, for the ^{222}Rn series and ^{212}Pb and ^{212}Bi (C_1 and C_2) for the thoron series. The constants are the fractional contributions of each decay product to the total potential alpha energy from the decay of unit activity of the gas. In this way, a measured radon concentration can be converted to an equilibrium equivalent concentration (EEC) directly proportional to PAEC. This provides a measure of exposure in terms of the product of concentration and time. The EEC can be converted to the PAEC, when desired, by the relationships 1 Bq m^{-3} = 5.56 10^{-6} mJ m^{-3} = 0.27 mWL (^{222}Rn) and 1 Bq m^{-3} = 7.6 10^{-5} mJ m^{-3} = 3.64 mWL (thoron).

123. Many measurements have been made of ^{222}Rn and decay product concentrations, allowing estimates to be made of the magnitude of the equilibrium factor to be estimated in terms of both typical values and range. These were discussed in previous reports of the Committee [U3, U4]. More recent extensive measurements in Europe [R1, W10], the United States [W2], Canada [B12], and Japan [H18, K9] indicate typical outdoor ^{222}Rn equilibrium factors of between 0.5 and 0.7. These results suggest that a rounded value of 0.6 may be more appropriate for the outdoor environment than the previous estimate of 0.8. There is, of course, a wide range of values from individual measurements, which is understandable given the many environmental factors that influence the various radionuclide activity ratios, including the exhalation rates and atmospheric stability conditions. The range of the equilibrium factor for outdoor radon is from 0.2 to 1.0, indicating a degree of uncertainty in the application of a typical value to derive equilibrium equivalent concentrations.

124. The equilibrium factor approach is more difficult to apply to estimate thoron decay product exposure because, unlike the ^{222}Rn situation, the concentrations of the gas and the decay products at any particular location, indoors or outdoors, may not be closely related. This is primarily due to the half-lives in the decay series, which produce very different distributions in the atmosphere of the gas and the decay products. A very limited amount of data on thoron decay product concentrations outdoors indicated a typical EEC of the order of 0.1 Bq m^{-3} [S4].

(b) Indoors

125. There is a wealth of data available on indoor ^{222}Rn concentrations, and new information is becoming available on indoor thoron. Substantial compilations of ^{222}Rn results appeared in the UNSCEAR 1988 and 1993 Reports [U3, U4]. These results are supplemented with recent survey data in Table 24. It is sometimes difficult to evaluate the representativeness of results from published reports. New information will be appearing from many countries in Africa, Asia, and South America, partly as a result of the Coordinated Research Programme on Radon in the Environment, sponsored by the International Atomic Energy Agency (IAEA). This will provide a better understanding of how different climates and housing patterns affect radon exposures. At this stage, it does not appear that the survey results have changed markedly from those contained in the UNSCEAR 1993 Report [U3]. In particular, the values of 40 and 30 Bq m^{-3} for the arithmetic and geometric means of the distribution of

worldwide indoor ^{222}Rn concentrations, with a geometric standard deviation of 2.3, still seem reasonable.

126. The geographic (latitudinal) variation in indoor radon concentration was considered in the UNSCEAR 1993 Report [U3]. Although levels at equatorial latitudes should reflect higher ventilation rates because of higher average outdoor temperatures, the general scatter in the results indicated that many other factors are involved. The additional data available from the present survey are included in Figure XIII.

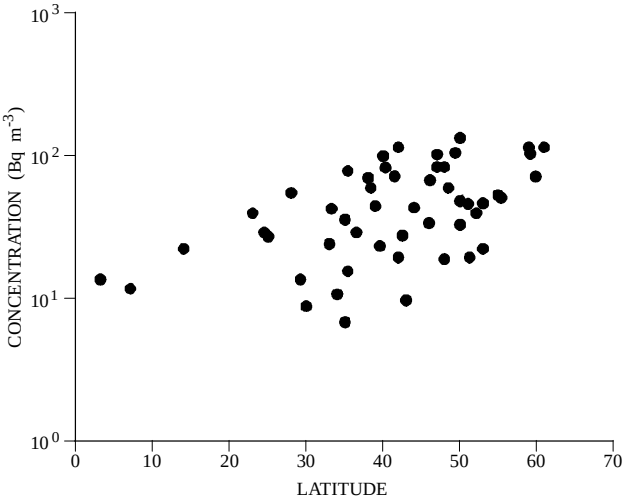

Figure XIII. Average concentrations of radon indoors in various countries in which measurements have been made in relation to latitude.

127. Recent determinations of the equilibrium factor for radon indoors generally confirm the typical value of 0.4 previously assessed by the Committee [U3, U4]. Indoor measurements show a range from 0.1 to 0.9, but most are within 30% of the typical value of 0.4 [H5, R2]. A recent study [H5] in seven North American houses has shown that the equilibrium factor in any building shows a significant variation with time, typically of a few tens of percent. Although the measurement of ^{222}Rn gas concentration may serve as a surrogate for direct measurement of the decay product concentrations in the determination of exposure, it is important to recognize that EECs or PAECs estimated in this manner for particular structures may be in error, frequently by several tens of percent and, rarely, by as much as a factor of 2.

128. Recent research has considerably clarified the situation with respect to indoor thoron and thoron decay product exposures. Several authors, e.g. [M2, N4, S4], have discussed the difficulties and uncertainties in measurements of such exposures and summarized the available data. It is not surprising, based on considerations discussed in previous paragraphs, that the limited data show a wide range of values. This may reflect measurement problems as well as real variations, since various techniques are used, and there has been much less international effort devoted to quality assurance for thoron than for ^{222}Rn. The large uncertainties are also due to the low concentrations usually encountered. The concentrations are highly variable in both space and time and are not closely coupled with the decay product concentrations at a particular location. For example, in a particular room of a structure, the thoron gas concentration varies considerably with distance from the walls and floor because of its short half-life [D1], while the decay products are homogeneously distributed in the room air. Moreover, the decay products were produced partly by thoron present hours earlier, the concentration of which might have been very different. There is, therefore, no surrogate for decay product measurement in the estimation of thoron exposure. This conclusion is supported by recent experimental [M2, M27] and calculational studies [Y2]. Earlier measurement data indicated that a thoron EEC of about 0.3 Bq m^{-3} is fairly typical of indoor atmospheres, although regional averages can be much higher or lower. This value was used in the UNSCEAR 1993 Report [U3].

129. Although measurements of thoron in indoor air are limited, most investigations have reported both the radon and thoron equilibrium equivalent concentrations, so some generalizations from the derived ratios can be made. Based on the physical characteristics of radon and thoron and model entry rates to buildings, ICRP estimated expected concentrations in buildings [I8]. These ranged from 10 to 100 Bq m^{-3} for radon and 2 to 20 Bq m^{-3} for thoron in typical circumstances (3–7 Bq m^{-3} for both radon and thoron in outdoor air; concrete and brick building material; a ventilation rate of 0.7 h^{-1}). In terms of EEC, these concentrations indoors are 2–50 Bq m^{-3} (mean = 15 Bq m^{-3}) for radon and 0.04–2 Bq m^{-3} (mean = 0.5 Bq m^{-3}) for thoron. This corresponds to an expected thoron-radon EEC ratio of 0.03.

130. From regional surveys in the United Kingdom [C26], the ratio of the PAECs of thoron to radon decay products ranged from 0.01 to 30. The highest value was obtained when the ventilation rate in the house was high (2.6 h^{-1}) and the radon concentration was unusually low (2.2 Bq m^{-3}). The distribution of values was approximately log-normal, and most values were between 0.1 and 2. For the wider survey region in the United Kingdom, including areas where high indoor radon concentrations occur, the geometric mean value of the ratio was 0.5. For more typical regions of the country, i.e. excluding the very radon-prone areas, the mean ratio was 0.3 [C26].

131. This ratio can also be expressed in terms of the EEC. The relationship between PAEC and EEC is as follows [I8]: $EEC_{Rn} = 1.81\ 10^8\ C_p$ and $EEC_{Th} = 1.32\ 10^7\ C_p$ for radon (^{222}Rn) and thoron (^{220}Rn) decay products, respectively. The relationships give the EEC with units of Bq m^{-3} when the potential alpha energy concentration, C_p, for either radon or thoron is expressed in J m^{-3}. The thoron-radon EEC ratio is thus lower than the PAEC ratio by a factor of 0.073, so that PAEC ratios of 0.3–0.5 correspond to EEC ratios of 0.02–0.04.

132. Available data on thoron EECs are given in Table 25. These are generally results of a few, short-term measure-

ments and are thus far less representative than the results for ^{222}Rn. Because of the short half-life of ^{220}Rn, the concentration of the gas varied greatly, as mentioned above, with distance from the soil surface or the structural material. Since such measurements cannot easily be standardized, there is little point in presenting data on concentrations of ^{220}Rn alone. The concentration of thoron decay products indoors are highest for wood-frame and mud houses, found particularly in Japan [D1, G12] or with the use of some building materials of volcanic origin, as found in some Italian regions [B25, S62].

133. The previously assumed representative concentrations of thoron EEC were 0.1 Bq m^{-3} outdoors and 0.3 Bq m^{-3} indoors [U3]. These values are at the lower range of values reported in Table 25, most of which were short-term measurements, but are in good agreement with the long-term measurements of Harley and Chittaporn [H36]. The thoron to radon EEC ratio determined in the United Kingdom (0.02) discussed above times the representative radon EEC indoors of 16 Bq m^{-3} (40 Bq m^{-3} × 0.4) would imply a representative value of the concentration of thoron indoors of 0.3 Bq m^{-3}. It thus seems justified to retain the above concentrations of thoron [U3] as representative. Further data are needed on the concentrations of thoron in air in order to provide a reliable estimate of the effective dose from thoron and its decay products.

134. The exposures and consequent doses from radon that are of interest in the assessment of health risks are those integrated over many years. It is well known that there are substantial time variations in the exposure rates from the decay products of both radon nuclides at any location, and each individual spends time at many locations, both indoors and outdoors, where exposure rates can be very different. Much of the published data on indoor ^{222}Rn concentrations is based on time-integrations of days (e.g. using charcoal canisters) to 3–12 months (e.g. using nuclear track detectors). There have been many studies of how short-term measurements can be used to estimate long-term exposures (see, for example, [P2]). One promising development has been the success of models based on outdoor temperature variations (effectively a surrogate for the indoor/outdoor temperature difference) in estimating and tracking the time variations of radon concentration in a few houses [H6]. Local meteoro-logical data can then be used to estimate long-term exposure. In Nordic countries, measurements made indoors in winter, when concentrations are higher because of strong advective air flows from soil, must be adjusted by a correction factor of 0.8 to estimate the annual mean radon concentrations [A12, M28, N12]. In the United Kingdom, correction factors of similar magnitude are needed for short-term measurements in winter and in the opposite direction for such measurements in summer to estimate the average annual concentrations [P11].

135. An important problem in epidemiological radon studies is to determine the long-term average radon levels that existed in the homes of the subjects under investigation. It has been proposed to measure ^{210}Po activities resulting from radon decay on glass surfaces [L2, L19, S52] or in volume traps [O10, S53]. The first technique is based on the deposition of airborne radon decay products onto smooth glass surfaces, followed by their subsequent recoil implantation. The second technique is based on the diffusion of radon throughout the bulk of spongy materials. The radon decay products are directly deposited inside the volume traps, where they remain until they are set free by means of a radiochemical separation procedure. Both of these techniques are promising [F19, M33].

136. The important distinction between “dwelling exposure assessment” and “person exposure assessment” was the subject of a recent experimental study in Austria [S5]. The six-month exposures of 34 individuals were measured with a personal radon meter and estimated from the particular exposure conditions and occupancy times at home, at work, and elsewhere. Results of the two assessments were found to differ by a factor of up to 3, and the possible reasons for these differences were explored. Judicious placement of monitors in the dwelling, for example in a bedroom rather than in the cellar, may reduce the differences between the two assessment approaches [H7].

137. In this Annex, as in previous UNSCEAR reports, typical exposures and exposure conditions are assessed for both indoor and outdoor environments, and doses are estimated from these results and estimated occupancy factors. This assessment is something like the dwelling exposure assessment: the basic assumption is that it reasonably describes typical exposure conditions averaged over large populations. As the population of interest becomes smaller, for example, cases and controls in an epidemiological study, the uncertainties in the assessment of individual and small group long-term exposures must be better understood and quantified.

138. In previous UNSCEAR reports, long-term radon exposures were estimated using indoor and outdoor occupancy factors of 0.8 and 0.2, respectively. These still seem to be reasonable estimates for the global population. However, for smaller population groups and individuals, the factors may be quite different.

3. Effective dose

139. Estimates of absorbed dose to the critical cells of the respiratory tract per unit ^{222}Rn exposure applicable to the general population can be derived from an analysis of information on aerosol size distribution, unattached fraction, breathing rate, fractional deposition in the airways, mucous clearance rate, and location of the target cells in the airways. Such estimates are model-dependent and necessarily subject to all of the uncertainties associated with the input data as well as the assumptions built into the particular calculational model.

140. For both radon-exposed underground miners and those exposed to other carcinogenic aerosols such as cigarette smoke, 75% of lung tumours are found in the branching

airways of the bronchial tree and 15% in the gas exchange region, or parenchyma [S36]. The dosimetry of inhaled radon and decay products is therefore directed to the cells of the bronchial epithelium. The most important variables affecting the alpha dose to the nuclei of these cells are the aerosol size distribution, the unattached fraction, the breathing rate, and the depth in tissue of the target cell nuclei. Considerable research has been conducted to determine quantitative values of the various biological and physical parameters required for lung dosimetry evaluation.

141. Upon decay of ^{222}Rn gas or in recoil from decay of the parent radionuclide, radon decay products are formed as small positive ions or neutral atoms approximately 0.5 nm in diameter. They increase rapidly to 0.5–5 nm as a result of clustering on water or other molecules in the air, depending on local conditions. The ultrafine aerosol mode is called the unattached fraction. Most of these small particles become attached to the local or ambient aerosol, 20–500 nm diameter, and this mode is called the attached fraction. The degree of attachment depends on the ambient aerosol concentration. In dusty, smoky conditions the unattached fraction will be very low, but in a very clean environment, such as prevails with air filtration, the unattached fraction can be much higher. Normally, only ^{218}Po is found in the unattached form with lower concentrations of unattached ^{214}Pb (^{214}Pb/^{218}Po = 1/10).

142. The unattached fraction of radon decay products is expressed as a fraction of the total potential energy (f_{pot}) [I18]. Other expressions have been used involving ratios of decay atoms, so care must be taken in interpreting the data. A central value of the unattached fraction in houses is f_{pot} = 0.05 [H5], but it can vary by a factor of 2 depending on local sources and air filtration.

143. Aerosol characteristics for the indoor environment have been documented by several investigators [B13, H5, N17, R18, T3, T17]. Although the ambient aerosol size in houses is about 100 nm on average, the diameter changes with indoor activities or sources. The use of electric motors, open flames, or electric heaters produces smaller aerosols with diameters of about 50 nm [T3]. Cigarette smoke produces aerosols about 300 nm in diameter [C23]. There is always a distribution of sizes present that can be well represented by a log-normal distribution with a geometric standard deviation of about 2.

144. Breathing rate is an important dosimetric factor because it controls the volume of air brought into the lungs. It can change the dose per unit concentration in air by a factor of about 2, with lower doses derived at lower breathing rates. The breathing rate varies, of course, with the degree of activity of the individual and is not easily measured. The breathing rate of an adult male was estimated to be 0.45 $m^3\ h^{-1}$ resting (8 h per day) and 1.2 $m^3\ h^{-1}$ in light activity (16 h per day) [I4]. The values for the adult female are 20% less resting and 5% less in light activity. The breathing rates were recently re-evaluated [I7], and somewhat lower averages values were derived, namely 22.2 $m^3\ d^{-1}$ for the adult male and 17.7 $m^3\ d^{-1}$ for the adult female.

145. The location of target cell nuclei in the bronchial epithelium has been measured in surgical specimens from over 100 persons of different sex, smoking history, and age [H8]. The average depth of basal and mucous cells implicated in carcinogenesis was 27 and 18 μm, respectively.

146. Deposition of aerosols in the bronchial airways has been investigated with replicate casts from human subjects. The detailed dimensions of the human bronchial airways were first reported by Yeh et al. [Y4] and later verified by Gurman et al. [G15]. Nasal deposition measurements of the unattached fraction is about 15% greater than oral deposition [C24]. Nasal deposition is approximately the same for both cyclic and steady air flow and for all ages. Deposition in the bronchial region occurs by diffusion for aerosol diameters less than 200 nm and by impaction for some particles of greater size. An empirical equation for deposition of aerosols in the upper bronchial airways was derived by Cohen et al. [C5] from measurements using replicate casts. Equations for deposition by impaction have also been derived [C10, G15, R6, R7].

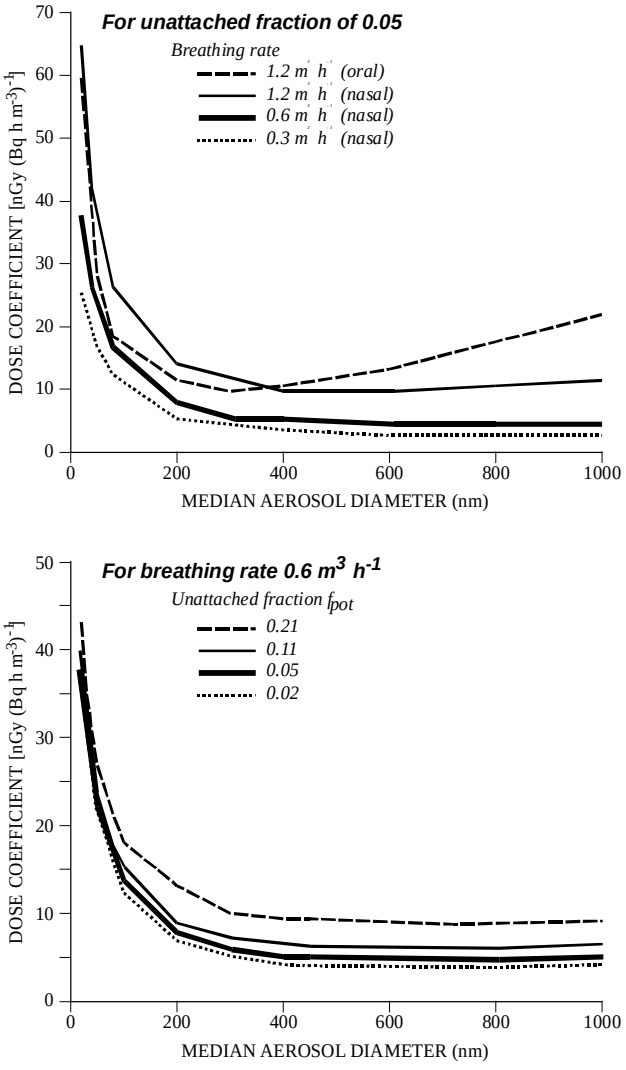

Figure XIV. Absorbed dose in bronchial epithelial cells per unit exposure (EEC) to radon.

147. Utilizing the latest and best available data for the various physical and biological parameters, dosimetrists have

calculated the absorbed dose per unit time-integrated EEC of radon in air. The results of Harley et al. [H8] are illustrated in Figure XIV. Since all particulate exposures contain a distribution of aerosol diameters rather than a unique or monodisperse size, it is more relevant to estimate the dose per unit exposure for a given median diameter and a geometric standard deviation σ_g. The results in Figure XIV are for distributions with $\sigma_g = 2$. The variation in dose with several different breathing rates is shown in the upper portion of Figure XIV for a specific unattached fraction $f_{pot} = 0.05$. The variation of dose with other values of the unattached fraction for a typical breathing rate (0.6 $m^3 h^{-1}$) is shown in the lower portion of Figure XIV. Similar variations are seen for other breathing rates.

148. The dosimetric evaluation of the absorbed dose to basal cells of the bronchial epithelium per unit exposure gives values in the range 5–25 nGy $(Bq\ h\ m^{-3})^{-1}$. The central value is estimated to be 9 nGy $(Bq\ h\ m^{-3})^{-1}$ for average indoor conditions, a breathing rate of 0.6 $m^3\ h^{-1}$, an aerosol median diameter of 100–150 nm and an unattached fraction of 0.05. For an apportioned tissue weighting factor of 0.08 for the bronchial and bronchiolar regions [I7] and the quality factor of 20, the effective dose per unit EEC is 15 nSv $(Bq\ h\ m^{-3})^{-1}$. The dose to the pulmonary region of the lungs is of much less significance.

149. ICRP has developed a more detailed lung model [I7] to calculate the effective dose for exposure to airborne radionuclides. It is, nevertheless, still a simplification of actual respiratory anatomy and physiological behaviour. This model is not yet recommended for radon and its decay products because of the discrepancy in results of risk derived from the model and from epidemiological studies. The difficulties include the measurement and specification of aerosol characteristics, including size and unattached fraction. The model is being used to assess the influence of biological and aerosol parameters and to characterize the uncertainties in estimates of the human lung dose [B11, Z3].

150. The results of major dosimetric studies of the lung dose from deposited ^{222}Rn decay products are compared in Table 26. Differences in the parameter values are evident, but consensus is beginning to emerge on the depth of the target cells, and the characterization of the airways and the deposition measurements based on accurate anatomical representation are greatly improving the dosimetry. With further progress, the derived dosimetric estimates can be expected to converge.

151. Efforts are being made to use measurement techniques based on wire screen penetration theory to simulate the particle collection properties of the nasal and tracheobronchial parts of the respiratory tract [H29]. Several radon progeny samplers for the direct determination of the lung dose have been developed [G19, J11, O2, S54]. Dose coefficients were derived from experimental data using both approaches [H5, H28, R21, S54, W2, Y7]. The results for different indoor and outdoor environments vary from 10 to 50 nSv $(Bq\ h\ m^{-3})^{-1}$. Similar results are obtained in sensitivity studies assessing the influence of biological and aerosol parameters on human lung dose [B11, M25, Z3].

152. As an alternative to a dosimetric approach, ICRP has derived a conversion convention for radon exposures based on the equality of detriments from epidemiological determinations. The nominal mortality probability coefficient for radon for males and females was taken to be 8 10^{-5} per mJ h m^{-3}. This value was determined from occupational studies of miners. Although the exposure conditions in mines are different from those in homes, the differences are compensating, e.g. lower unattached fractions and higher breathing rates in mines than in homes. This coefficient was related to the detriment per unit effective dose, chosen to be 5.6 10^{-5} per mSv for workers and 7.3 10^{-5} per mSv for the public [I1]. The values of the conversion convention are thus 8 10^{-5} ÷ 5.6 10^{-5} = 1.43 mSv $(mJ\ h\ m^{-3})^{-1}$ (5.06 mSv WLM^{-1}) for workers and 8 10^{-5} ÷ 7.3 10^{-5} = 1.10 mSv $(mJ\ h\ m^{-3})^{-1}$ (3.88 mSv WLM^{-1}) for members of the public. The rounded values adopted by ICRP are 1.4 and 1.1 mSv $(mJ\ h\ m^{-3})^{-1}$ (5 and 4 mSv WLM^{-1}) at work and at home, respectively [I6]. The latter value corresponds to 6 nSv $(Bq\ h\ m^{-3})^{-1}$, which is different by a factor of 2.5 from the central value derived using the dosimetric approach. This is not a big discrepancy, considering the complex physical and biological issues involved.

153. The range of dose conversion factors for radon, derived from epidemiological studies [I6] and physical dosimetry, varies from 6 to 15 nSv $(Bq\ h\ m^{-3})^{-1}$. The previous value applied in the UNSCEAR 1993 Report was 9 nSv $(Bq\ h\ m^{-3})^{-1}$. Updated and additional epidemiological studies of 11 underground mining cohorts [C33], performed subsequently to the calculation made in [I6], suggests an increased radon risk per unit exposure. Therefore an increase in the epidemiologically based dose conversion convention is anticipated. The domestic epidemiological radon studies do not yet have sufficient precision to provide numerical risk estimates that could be used in an epidemiological dose conversion convention. Given the present range of values of the dose conversion factor, the established value of 9 nSv $(Bq\ h\ m^{-3})^{-1}$, used in past UNSCEAR calculations [U3, U4], is still considered appropriate for average effective dose calculations. For the representative concentrations of radon selected in Section II.C.2, equilibrium factors of 0.4 indoors and 0.6 outdoors, occupancy, and the dose coefficient as given above, the following annual effective doses are derived:

Indoors: $40\ Bq\ m^{-3} \times 0.4 \times 7{,}000\ h \times 9\ nSv\ (Bq\ h\ m^{-3})^{-1} = 1.0\ mSv$

Outdoors: $10\ Bq\ m^{-3} \times 0.6 \times 1{,}760\ h \times 9\ nSv\ (Bq\ h\ m^{-3})^{-1} = 0.095\ mSv$

154. Less work has been done to derive the dose coefficient for thoron. The values used in the UNSCEAR 1993 Report [U3] were 10 nSv $(Bq\ h\ m^{-3})^{-1}$ for exposures outdoors and 32 nSv $(Bq\ h\ m^{-3})^{-1}$ indoors. Applying the new lung model [I7] results in significantly higher values. There are no epidemiological data for lung cancer risk following thoron exposure from which to derive a conversion convention for

thoron decay products similar to that for radon decay products. The value of 40 nSv (Bq h m^{-3})$^{-1}$ for equilibrium equivalent concentrations of thoron, derived in Annex A, "*Dose assessment methodologies*", seems appropriate for evaluating exposures both indoors and outdoors.

155. The concentration of ^{220}Rn is about 10 Bq m^{-3} outdoors and approximately the same indoors. However, it is not possible to use the concentration of the gas in dose evalua-tion, since the concentration is strongly dependent on the distance from the source. Starting with the assumed represen-tative equilibrium equivalent concentrations, as discussed above, the annual effective dose may be derived as follows:

Indoors: 0.3 Bq m^{-3} (EEC) × 7,000 h × 40 nSv (Bq h m^{-3})$^{-1}$ = 0.084 mSv

Outdoors: 0.1 Bq m^{-3} (EEC) × 1,760 h × 40 nSv (Bq h m^{-3})$^{-1}$ = 0.007 mSv

The average annual effective dose from thoron decay products is thus estimated to be 0.09 mSv.

156. For completeness, the contributions to effective dose from two relatively minor pathways of exposure to radon and thoron can be added, namely dissolution of the gases in blood with distribution throughout the body and the presence of radon in tap water. The dose coefficients for radon and thoron dissolved in blood following inhalation intake are those used in the UNSCEAR 1993 Report [U3]. The dose estimate for radon is

Indoors: 40 Bq m^{-3} × 7,000 h × 0.17 nSv (Bq h m^{-3})$^{-1}$ = 0.048 mSv

Outdoors: 10 Bq m^{-3} × 1,760 h × 0.17 nSv (Bq h m^{-3})$^{-1}$ = 0.003 mSv

For thoron, it is

Indoors: 10 Bq m^{-3} × 7,000 h × 0.11 nSv (Bq h m^{-3})$^{-1}$ = 0.008 mSv

Outdoors: 10 Bq m^{-3} × 1,760 h × 0.11 nSv (Bq h m^{-3})$^{-1}$ = 0.002 mSv.

157. Radon in tap water may lead to exposures from the ingestion of drinking water and from the inhalation of radon released to air when water is used. The concentration of radon in water and the release to air were discussed earlier. Although the calculated result is shown below, this is not a separate contribution to the effective dose, since the radon source from water usage would have been included in the measured indoor radon concentrations. The parameters for the inhalation pathway were presented in paragraph 114: concentration in water of 10 kBq m^{-3}, air-water concentration ratio of 10^{-4}, indoor occupancy of 7,000 hours per year. The inhalation dose coefficient applied is that for the gas. The ingestion of tap water was estimated in the UNSCEAR 1993 Report [U3] to be 100, 75, and 50 l a^{-1} by infants, children, and adults. Assuming the proportion of these groups in the population to be 0.05, 0.3, and 0.65, the weighted estimate of consumption is 60 l a^{-1}. A conservative estimate of the ingestion dose coefficient has recently been evaluated [N10]. The estimated exposures from radon in water are therefore

Inhalation: 10 kBq m^{-3} × 10^{-4} × 7,000 h × 0.4 × × 9 nSv (Bq h m^{-3})$^{-1}$ = 0.025 mSv

Ingestion: 10 kBq m^{-3} × 60 l a^{-1} × 10^{-3} m^3 l^{-1} × × 3.5 nSv Bq^{-1} = 0.002 mSv.

158. The total annual effective dose from radon is thus 1.1 mSv from inhalation of ^{222}Rn and its decay products present in air from all sources, 0.05 from radon gas dissolved in blood, and 0.002 from radon gas in ingested tap water (total = 1.15 mSv). The estimates for thoron are 0.09 from inhalation of ^{220}Rn and its decay products and 0.01 from thoron gas dissolved in blood (total = 0.10 mSv).

159. Considering the range of radon exposures determined from survey data and the generally log-normal distribution of such exposures in particular areas, one would expect to find many large populations around the world (~10^6 individuals) whose average exposures differ from the above-estimated global averages by a factor of more than 2, and many smaller populations (~10^4 individuals) whose average exposures differ by a factor of more than 10. Thus the estimates of the global averages are significant primarily because they define the normal radon and thoron exposures and typical effective doses.

III. ENHANCED EXPOSURES FROM INDUSTRIAL ACTIVITIES

160. There are a number of circumstances in which materials containing natural radionuclides are recovered, processed, used, or brought into position such that radiation exposures result. This human intervention causes extra or enhanced exposures. Although any indoor exposure from building materials surrounding the body would fall in this category, such an exposure is considered a normal component of the natural radiation background. The exposures generally included in the category of enhanced exposures are those arising from the mineral processing industries and from fossil fuel combustion.

161. The Committee generally reviews enhanced exposures in its evaluations of natural radiation sources, as in the latest assessment in the UNSCEAR 1993 Report [U3]. The contribution to the total exposure is usually rather minimal. The UNSCEAR 1982 Report [U6] provided more detailed review of enhanced exposures from natural sources, referring to them at that time as technologically modified exposures. There are also some practices that lead to diminished exposures such as paving roads and using building materials of low radioactive content. These alterations in exposures are usually of less significance than those that cause enhanced exposures.

162. In general, the topic of enhanced exposures is receiving greater attention with several meetings devoted to this subject having recently taken place and several publications issued, e.g. [B26, E6, E7, K20, K21, M34]. Since the Committee has not yet undertaken a wider review of this subject, the reader is referred to the topical publications and proceedings for updated information.

163. In this Chapter, exposures of the general public arising from emissions of naturally occurring radionuclides to the environment from industrial activities are reviewed. Industry uses many different raw materials that contain naturally occurring radioactive materials, sometime abbreviated NORM. These raw materials are mined, transported, and processed for further use. The consequent emissions of radionuclides to air and water lead to the eventual exposure of humans. The main industries are identified below, along with the raw materials and by-products or wastes they generate. The radionuclide content of these raw materials and wastes is summarized in Table 27.

164. ***Phosphate processing***. This industry may be sub-divided into (a) wet processing, (b) thermal processing, and (c) fertilizer production. The primary product is phosphoric acid. In the thermal process, the product may be phosphorus or, using nitric acid, phosphoric acid. Phosphoric acid is used in the manufacture of fertilizers. In the wet phosphate processing industry, phosphogypsum is produced as a by-product. The thermal process (using cokes and silica) produces a slag ($CaSiO_2$) as a waste product.

165. ***Metal ore processing***. Important metal ores are cassiterite or tinstone (tin), tantalite, columbite, fergusonite, koppite, samarskite, and pyrochlore (niobium, iron, manganese, and others). Most of the metals are separated using charcoal or coke. Furnace slag from the processing is often used in cement production. Another by-product, tar coal, is used to produce electrode pitch, creosote oil, carbolineum, soot oil, and road tar mix.

166. ***Uranium mining***. There are several locations that contain the residues of former uranium mining operations, for example, in eastern Germany [B29, E9, R23]. The procedures to deal with the landfills, waste rock and slag piles and the radiological consequences are being evaluated.

167. ***Zircon sands***. Important zirconium minerals are zircon ($ZrSiO_4$) and baddeleyite (ZrO_2). Sorting discriminates these minerals from other heavy minerals or simple silica. The processing involves procedures such as sieving, washing, drying, and grinding. These processes do not produce any specific waste products.

168. ***Titanium pigment production***. Titanium pigments include titanium dioxide (TiO_2) and synthetic rutile. Processing waste products include large quantities of cokes, ore and SiO_2 particles, and filter cake (classified as chemical waste).

169. ***Fossil fuels***. For electric power production the most important fossil fuels are coal, natural gas, and oil. Large amounts of fly ash and bottom ash result from coal combustion. Gypsum is recovered if a desulphurization installation is present.

170. ***Oil and gas extraction***. The large volumes of production water needed for the extraction of oil and gas may contain natural radionuclides, mainly ^{226}Ra and its decay products. Scalings may form as a result of precipitation at the oil/water interface, or radon decay products (especially ^{210}Pb and ^{210}Po) may be deposited in the installations.

171. ***Building materials***. Materials used by the building industry that may be of radiological significance include marl, blast furnace slag, fly ash, Portland clinker, and anhydrate (in the cement industry) and clay (in the ceramics industry). In the cement industry, some silex is produced as a waste product.

172. ***Thorium compounds***. Thorium is used mainly as an additive in other products, such as welding electrodes, gas mantles, and special alloys and is retrieved from monazite, thorite, or thorianite. The activity content of the compounds is present mainly in the primary product, metallic thorium.

173. ***Scrap metal industry***. Scrap metal such as tubing, valves, and heat exchangers from various process industries may contain scales with enhanced levels of natural radionuclides. The particular radionuclides and their concentrations would depend on the origin of the scrap. Since objects from nuclear industries and the uncontrolled releases of radioactive sources may add to this material, which may be recycled, the scrap-metal industry is a source of variable and heterogenous releases of radionuclides into the environment.

174. ***Emissions***. The natural radionuclides present in the raw materials or wastes of these industries are those of the ^{238}U and ^{232}Th series. Releases are mainly to air or water, although landfills after dredging or wastes disposed on land may also provide pathways of exposure.

175. Emissions of radionuclides to air and water from these industries are listed in Table 28. The throughput of ore or raw material is for a typical installation. One of the main radionuclides released to air is ^{222}Rn. It is released by the phosphate and cement industries, gas and oil extraction, gas-fired power production, and, generally, industries that burn natural gas. For example, in the phosphate industry, enhanced radon concentrations between 35 and 780 Bq m^{-3} have been observed, depending on the working area and season [V6]. Important sources of ^{210}Pb to air are the elementary phosphorus and iron and steel production industries. Cement production gives rise to much of the ^{210}Po released. Brick and tile installations may also be of importance because they are so numerous.

176. A special problem is imposed by the storage of uranium-containing minerals in museums [V6]. In a museum in Brussels, where radium- and uranium-containing minerals

from Katanga were stored, concentrations of radon of about 10–15 kBq m^{-3}were found in spite of enhanced ventilation. Besides radon emissions, high levels of gamma radiation were also observed in the vicinity of the storage rooms. In the house of the museum caretaker who lived nearby, gamma levels of 5–6 μSv h^{-1} were found. After shielding of the minerals, the radiation level was reduced to 1–2 μSv h^{-1}.

177. The radionuclides released to the atmosphere by large thermal processes such as those used by elementary phosphorus production, iron and steel production, and the cement industry, are dispersed over great distances. Smaller thermal processes, such as the brick and tile industry, are also sources of airborne releases. For other mineral processing industries, dusty conditions during handling and shipment of ores are the main reason for the releases of radionuclides to air. In those circumstances, the rather coarse particles are generally released mainly to the immediate surroundings of the plant.

178. The largest releases of radionuclides to water are from the phosphate processing, followed by oil and gas production and primary iron and steel production. As an example, two phosphoric acid plants in the Netherlands are responsible for some 90% of all discharges of ^{210}Pb and ^{210}Po to water [L18]. These two plants release about 0.6–0.8 TBq of ^{226}Ra per year [L24], which is comparable to the estimated annual release of ^{226}Ra with process water into the North Sea by the offshore oil production industry in the United Kingdom, Norway, the Netherlands, and Denmark [L25]. Annual releases into rivers of ^{226}Ra and of ^{228}Ra present in diluted brines from single Upper Silesian coal mines may be as high as 20 and 30 GBq, respectively, resulting in locally enhanced concentrations in bottom sediments [L26, S63].

179. The large amounts of gypsum slurry discharged in phosphoric acid production may be released into the sea as is the case in the Netherlands, but industrial wastes are sometimes also stored on land or in large landfills. Radionuclides released to water in, for example, discharges from oil and gas extraction offshore are generally diluted by the large volumes of water involved. Onshore process water is often pumped back into the oilfield. The treatment of production waters before they are released may significantly reduce the radionuclide concentration [L26].

180. Enhanced levels of radionuclides in the environment can come from the processing and use of scrap and recycled metals [B28, L22]. Although in general extensive measures are taken to ensure the continuous quality of the scrap and the new metal that is manufactured from it, enhanced radiation levels are sometimes found. The number of reports on such incidents is growing, partly because of increased awareness of the problem and partly because more measurements are being made. The enhanced exposures may arise from lost radium radiation sources or from naturally occurring radionuclides in pipes with scale containing enhanced concentrations [T15]. Similar problems arise from man-made sources, for example, ^{22}Na, ^{54}Mn [W15], ^{60}Co [C31], ^{137}Cs [B27, J12] or ^{192}Ir, leading to contaminated scrap and recycled metals. The levels vary greatly, and the consequences depend on specific local circumstances.

181. ***Exposures***. Both external and internal exposures may result from naturally occurring radionuclides released by industrial activities. In general, installations are located away from residential areas, and because external radiation levels decrease with distance from the plant, local residents are not significantly exposed. The workers, however, may receive low doses in connection with ore stock piles or waste deposits. Estimated and measured doses are in the range 0.1–300 μSv a^{-1} from direct exposures, with the higher values for locations near mineral-sands-handling industries. The maximum effective doses are summarized in Table 29.

182. Radionuclides dispersed in air may contribute to external irradiation while airborne and after deposition. The contributions to total dose appear to be negligible. Inhalation and ingestion are the pathways that contribute to internal exposure. Inhalation contributes to exposure only in the vicinity of the plant, particularly with mineral-sands-processing plants. Doses depend on distance and could be up to 50 μSv a^{-1} for office workers in a building just outside the plant site [L18].

183. Because most food products consumed by individuals are produced in large agricultural regions, possible dose from ingestion of radionuclides are small. For a typical situation, a small population in the vicinity of an elementary phosphorus plant, the calculated dose would be of the order 100 μSv a^{-1} [L18]. More generally, the estimated doses would be 1–10 μSv a^{-1}. Ingestion doses that could result from discharges of wastes to water are negligible compared to those by the other pathways.

184. In the United Kingdom, the doses from sintering plants of the steel industry to critical groups of the population were calculated to be between about 1.5 and 18 μSv a^{-1}. The highest dose was attributed to a sinter site with relatively low stacks. Inhalation contributed less than 22%, with the main exposure route being the ingestion of food. The annual collective dose calculated for the population (to a distance of 3,000 km) was estimated to be between about 2.9 and 5.5 man Sv [H33].

185. Penfold et al. [P10] made a pilot study of the radiological impact of coal-fired stations in the United Kingdom. Various pathways of exposure were considered. The highest dose rate for a critical group (about 250 μSv a^{-1}) came from the use of fly ash in building materials. Other pathways caused dose rates for critical groups between 0.07 and 55 μSv a^{-1}.

186. The radiation exposure of critical groups of the population surrounding a site with a wood-chip-burning oven was determined in a Swedish study [H34]. The maximum individual dose rate was found to be 2.4 nSv a^{-1}.

187. Annual per caput effective doses from process industries documented in the UNSCEAR 1993 Report ranged from 1 nSv to 20 μSv and for critical groups up to about 1 mSv. Those mentioned above and other more recent data are for very specific situations or critical groups. On the whole, however, they are in agreement with the earlier estimates, and they support the conclusions of the UNSCEAR 1993 Report [U3].

188. ***Summary***. The industrial activities enhancing exposure from natural sources involve large volumes of raw materials containing natural radionuclides. Discharges from industrial plants to air and water and the use of by-products and waste materials may be the main contributors to enhanced exposure of the general public. For typical industries and releases, exposures occur primarily in close proximity to the plants. A complete review is made difficult by the diversity of industries involved and the local circumstances associated with the exposures. Estimated maximum exposures are greatest for phosphoric acid production and the mineral-sands-processing industries. Although exposure rates of the order of 100 μSv a^{-1} could be received by a few local residents, levels of 1–10 μSv a^{-1} would be more common. These exposure rates constitute a negligible component of the total annual effective dose from all natural sources of radiation.

IV. WORLDWIDE AVERAGE EXPOSURE FROM NATURAL SOURCES

189. The components of exposure caused by natural radiation sources have been reassessed in this Annex based on new information and data from measurements and on further analysis of the processes involved. These exposure components can now be added to provide an estimate of the total average exposure. It must first be stated that the average exposure probably does not pertain to any one individual, since there are wide distributions of exposures from each source and the exposures combine in various ways at each location, depending on the specific concentrations of radionuclides in the environment and in the body, the latitude and altitude of the location, and many other factors.

190. In a few countries the proportion of the population at various levels of total exposures has been assessed. These data are included in Table 30, and the combined distribution is shown in Figure XV. The average annual exposure for this distribution is 2.0 mSv. The distribution rises in a few dose intervals to the peak exposure and then tails off to decreasing population at doses 2 to 3 times the average. To smooth the distribution somewhat, most exposure intervals have been subdivided. The general shape of the distribution is probably fairly relevant. Although populations living in areas of high background exposures are not well represented in this particular distribution, they would not be expected to be a prominent feature, in part because not all components of their exposure are enhanced at the same time and because there is a relatively small proportion of the population of most countries with significantly elevated exposures.

191. Average worldwide exposure determined by adding the various components is summarized in Table 31. The changes from the earlier assessment of the Committee [U3] are also indicated. There are only rather minor changes for the exposure components. The worldwide average annual exposure to natural radiation sources remains 2.4 mSv. Neither the magnitude nor the precision of this estimate should be overemphasized. As indicated in Figure XV, based on the sample population of Table 30, a broad distribution of exposures would be expected in any large population.

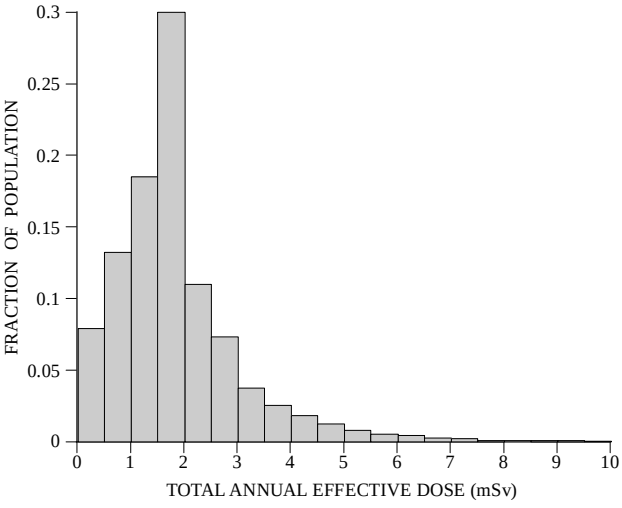

Figure XV. Distribution of population of fifteen countries with respect to total annual effective dose.

192. The normal ranges of exposures to the various components of natural radiation are indicated in Table 31. This accounts for common variations in exposures but excludes those individuals at the extreme ends of the distributions. On this basis, worldwide annual exposures to natural radiation sources would generally be expected to be in the range 1–10 mSv, with 2.4 mSv being the present estimate of the central value.

CONCLUSIONS

193. Since exposures to natural radiation sources are more significant for the world's population than most exposures to man-made sources, the natural background baseline warrants evaluation in some detail. Efforts should continue to broaden the database used for determining both representative values and extremes in exposures and to improve dosimetric procedures.

194. Because of the wide variations in natural background exposures even within relatively small regions, more efforts will be required to determine the detailed distributions of populations within dose intervals for the various components of exposure. Initial, still limited evaluations of distributions of external exposures outdoors and indoors and of the total exposure have been presented in this Annex. These evaluations seem to reveal patterns that would be expected to be generally valid for other countries and for the world population as a whole. The analysis of distributions will provide an improved basis for deriving worldwide average exposures and their normal and extreme variations.

195. The main uncertainties in the assessment of dose from natural radiation sources arise less from the limited number of measurements than from the complications of the dosimetric considerations. The situation with respect to radon decay products is well known, but similar problems exist for cosmic radiation and ingested radionuclides. For cosmic radiation, more information is needed on exposures to neutrons at all altitudes and latitudes, especially high-energy neutrons and high-Z nuclei at aircraft altitudes, along with critical data or improved models to allow a reasonable estimation of effective doses from these components of the radiation field. For ingested radionuclides, good dosimetric models are available, but the problem is to estimate representative intake amounts of the radionuclides and associate them with relatively fewer determinations of concentrations in tissues of the body.

196. There are many circumstances in which individuals receive enhanced exposures to natural radiation. Living inside buildings is considered normal in this regard, and flying in airplanes usually involves an insignificant proportion of most people’s time. In the past, the Committee has reviewed the exposures caused from the release of natural radionuclides in mineral processing industries, the use of phosphate fertilizers, and the combustion of fossil fuels. These enhanced exposures are usually quite insignificant compared with the normal background exposure from natural sources. This conclusion is still valid, based on a brief review of new information in this Annex.

197. The evaluations in this Annex of exposures from natural radiation sources indicate that the average annual effective dose to the world population is approximately 2.4 mSv, which is the same as the previous estimate of the Committee [U3]. The value of the estimated average exposure should not be taken to be too precise, since broad averaging is involved. For individuals, annual exposures ranging from 1 mSv to two or three times the world average are frequently encountered. It is estimated that about 65% of individuals have exposures between 1 and 3 mSv, about 25% of the population have exposures less than 1 mSv, and 10% have exposures greater than 3 mSv. Although the database continues to expand and characterization of the distributions of populations with respect to the various components of natural background radiation is being improved, the generally assessed exposure levels to which the broad spectrum of the world population is exposed seem reasonably well substantiated.

Table 1
Latitude distribution of cosmic ray dose rates outdoors at sea level

Latitude (degrees)	*Population in latitude band (%)*		*Effective dose rate (nSv h^{-1})*	
	Northern hemisphere	*Southern hemisphere*	*Directly ionizing component* [a]	*Neutron component* [b]
80–90	0	0	32	11
70–80	0	0	32	11
60–70	0.4	0	32	10.9
50–60	13.7	0.5	32	10.0
40–50	15.5	0.9	32	7.8
30–40	20.4	13.0	32	5.3
20–30	32.7	14.9	30	4.0
10–20	11.0	16.7	30	3.7
0–10	6.3	54.0	30	3.6
Total	100	100		
Population-weighted average				
Northern hemisphere			31.0	5.6
Southern hemisphere			30.3	4.0
World [c]			30.9	5.5

a Average measurement results.
b From fit to measurements of Figure II.
c Population distribution: northern hemisphere 0.89; southern hemisphere 0.11.

Table 2
Population-weighted average cosmic ray dose rates

Conditions	*Effective dose rate (μSv a^{-1})*						
	Directly ionizing component			*Neutron component*			*Total*
	North	*South*	*World*	*North*	*South*	*World*	*World*
Outdoors, at sea level	272	265	270	49	35	48	320
Outdoors, altitude adjusted [a]	339	332	340	124	87	120	460
Altitude, shielding, occupancy adjusted [b]	285	279	280	104	73	100	380

a Altitude-weighting factors applied to sea level values: directly ionizing component 1.25; neutron component 2.5.
b Building shielding factor 0.8; indoor occupancy factor 0.8.

Table 3
Physical data for radionuclides of natural origin
[F6]

Element	*Isotope*	*Half-life*	*Decay mode*
Cosmogenic radionuclides			
Hydrogen	^{3}H	12.33 a	beta (100%)
Beryllium	^{7}Be	53.29 d	EC [a] (100%)
	^{10}Be	$1.51\ 10^{6}$ a	beta (100%)
Carbon	^{14}C	5730 a	beta (100%)
Sodium	^{22}Na	2.602 a	EC (100%)
Aluminium	^{26}Al	$7.4\ 10^{5}$ a	EC (100%)
Silicon	^{32}Si	172 a	beta (100%)
Phosphorus	^{32}P	14.26 d	beta (100%)
	^{33}P	25.34 d	beta (100%)
Sulphur	^{35}S	87.51 d	beta (100%)
Chlorine	^{36}Cl	$3.01\ 10^{5}$ a	EC(1.9%), beta (98.1%)
Argon	^{37}Ar	35.04 d	EC (100%)
	^{39}Ar	269 a	beta (100%)
Krypton	^{81}Kr	$2.29\ 10^{5}$ a	EC (100%)
Terrestrial radionuclides			
Potassium	^{40}K	$1.28\ 10^{9}$ a	beta (89.3%), EC (10.7%)
Rubidium	^{87}Rb	$4.75\ 10^{10}$ a	beta (100%)
Lanthanum	^{138}La	$1.05\ 10^{11}$ a	beta (33.6%), EC (66.4%)
Samarium	^{147}Sm	$1.06\ 10^{11}$ a	alpha (100%)
Lutecium	^{176}Lu	$3.73\ 10^{10}$ a	beta (100%)
^{238}U series:			
Uranium	^{238}U	$4.47\ 10^{9}$ a	alpha (100%)
Thorium	^{234}Th	24.10 d	beta (100%)
Protactinium	^{234m}Pa	1.17 m	beta (99.8%), IT [b]
Uranium	^{234}U	$2.45\ 10^{5}$ a	alpha (100%)
Thorium	^{230}Th	$7.54\ 10^{4}$ a	alpha (100%)
Radium	^{226}Ra	1600 a	alpha (100%)
Radon	^{222}Rn	3.824 d	alpha (100%)
Polonium	^{218}Po	3.05 m	alpha (99.98%), beta (0.02%)
Lead	^{214}Pb	26.8 m	beta (100%)
Bismuth	^{214}Bi	19.9 m	alpha (0.02), beta (99.98%)
Polonium	^{214}Po	164 µs	alpha (100%)
Lead	^{210}Pb	22.3 a	beta (100%)
Bismuth	^{210}Bi	5.013 d	beta (100%)
Polonium	^{210}Po	138.4 d	alpha (100%)
Lead	^{206}Pb	stable	
^{232}Th series:			
Thorium	^{232}Th	$1.405\ 10^{10}$ a	alpha (100%)
Radium	^{228}Ra	5.75 a	beta (100%)
Actinium	^{228}Ac	6.15 h	beta (100%)
Thorium	^{228}Th	1.912 a	alpha (100%
Radium	^{224}Ra	3.66 d	alpha (100%)
Radon	^{220}Rn	55.6 s	alpha (100%)
Polonium	^{216}Po	0.145 s	alpha (100%)
Lead	^{212}Pb	10.64 h	beta (100%)
Bismuth	^{212}Bi	60.55 m	alpha (36%), beta (64%)
Polonium	^{212}Po	0.299 µs	alpha (100%)
Thalium	^{208}Tl	3.053 m	beta (100%)
Lead	^{208}Pb	stable	
^{235}U series:			
Uranium	^{235}U	$7.038\ 10^{8}$ a	alpha (100%)
Thorium	^{231}Th	25.52 h	beta (100%)
Protactinium	^{231}Pa	32760 a	alpha (100%)
Actinium	^{227}Ac	21.77 a	alpha (1.4%), beta 98.6%)
Thorium	^{227}Th	18.72 d	alpha (100%)
Francium	^{223}Fr	21.8 m	beta (100%)
Radium	^{223}Ra	11.44 d	alpha (100%)
Radon	^{219}Rn	3.96 s	alpha (100%)
Polonium	^{215}Po	1.781 ms	alpha (100%)
Lead	^{211}Pb	36.1 m	beta (100%)
Bismuth	^{211}Bi	2.14 m	alpha (99.7%), beta 0.3%)
Thalium	^{207}Tl	4.77 m	beta (100%)
Lead	^{207}Pb	stable	

a Electron capture.
b Internal transition.

Table 4
Production rates and concentrations of cosmogenic radionuclides in the atmosphere

Radionuclide	*Production rate*		*Global inventory (PBq)*	*Fractional amount in troposphere* [a]	*Concentration in troposphere* [b] *(mBq m^{-3})*
	Per unit area [a] *(atoms m^{-2} s^{-1})*	*Annual amount* [c] *(PBq a^{-1})*			
^{3}H	2 500	72	1 275	0.004	1.4
^{7}Be	810	1 960	413	0.11	12.5
^{10}Be	450	0.000064	230	0.0023	0.15
^{14}C	25 000	1.54	12 750	0.016	56.3
^{22}Na	0.86	0.12	0.44	0.017	0.0021
^{26}Al	1.4	0.000001	0.71	7.7 10^{-8}	1.5 10^{-8}
^{32}Si	1.6	0.00087	0.82	0.00011	0.000025
^{32}P	8.1	73	4.1	0.24	0.27
^{33}P	6.8	35	3.5	0.16	0.15
^{35}S	14	21	7.1	0.08	0.16
^{36}Cl	11	0.000013	5.6	6 10^{-8}	9.3 10^{-8}
^{37}Ar	8.3	31	4.2	0.37	0.43
^{39}Ar	56	0.074	28.6	0.83	6.5
^{81}Kr	0.01	1.7 10^{-8}	0.005	0.82	0.0012

a References [L5, L6].
b Assumes tropospheric volume of 3.62275 10^{18} m^3; inferred from [L5].
c Assumes surface area of world = 5.1005 10^{14} m^2 [L14].

Table 5
Natural radionuclide content in soil
Data not referenced are from UNSCEAR Survey of Natural Radiation Exposures

Region / country	*Population in 1996 (10^6)*	*Concentration in soil (Bq kg^{-1})*							
		^{40}K		*^{238}U*		*^{226}Ra*		*^{232}Th*	
		Mean	*Range*	*Mean*	*Range*	*Mean*	*Range*	*Mean*	*Range*
Africa									
Algeria	28.78	370	66–1 150	30	2–110	50	5–180	25	2–140
Egypt	63.27	320	29–650	37	6–120	17	5–64	18	2–96
North America									
Costa Rica	3.50	140	6–380	46	11–130	46	11–130	11	1–42
United States [M7]	269.4	370	100–700	35	4–140	40	8–160	35	4–130
South America									
Argentina	35.22	650	540–750						
East Asia									
Bangladesh	120.1	350	130–610			34	21–43		
China [P16, Z5]	1232	440	9–1 800	33	2–690	32	2–440	41	1–360
– Hong Kong SAR [W12]	6.19	530	80–1 100	84	25–130	59	20–110	95	16–200
India	944.6	400	38–760	29	7–81	29	7–81	64	14–160
Japan [M5]	125.4	310	15–990	29	2–59	33	6–98	28	2–88
Kazakstan	16.82	300	100–1 200	37	12–120	35	12–120	60	10–220
Korea, Rep. of	45.31	670	17–1 500						
Malaysia	20.58	310	170–430	66	49–86	67	38–94	82	63–110
Thailand	58.70	230	7–712	114	3–370	48	11–78	51	7–120
West Asia									
Armenia	3.64	360	310–420	46	20–78	51	32–77	30	29–60
Iran (Islamic Rep. of)	69.98	640	250–980			28	8–55	22	5–42
Syrian Arab Republic	14.57	270	87–780	23	10–64	20	13–32	20	10–32

Table 5 (continued)

Region / country	*Population in 1996 (10^6)*	*Concentration in soil (Bq kg^{-1})*							
		^{40}K		*^{238}U*		*^{226}Ra*		*^{232}Th*	
		Mean	*Range*	*Mean*	*Range*	*Mean*	*Range*	*Mean*	*Range*
North Europe									
Denmark [N5]	5.24	460	240–610			17	9–29	19	8–30
Estonia	1.47	510	140–1 120			35	6–310	27	5–59
Lithuania	3.73	600	350–850	16	3–30			25	9–46
Norway	4.35	850		50		50		45	
Sweden	8.82	780	560–1 150			42	12–170	42	14–94
West Europe									
Belgium	10.16	380	70–900			26	5–50	27	5–50
Germany	81.92		40–1 340		11–330		5–200		7–134
Ireland [M6]	3.55	350	40–800	37	8–120	60	10–200	26	3–60
Luxembourg	0.41	620	80–1 800			35	6–52	50	7–70
Netherlands [K2]	15.58		120–730		5–53	23	6–63		8–77
Switzerland	7.22	370	40–1 000	40	10–150	40	10–900	25	4–70
United Kingdom [B2]	58.14		0–3 200		2–330	37			1–180
East Europe									
Bulgaria	8.47	400	40–800	40	8–190	45	12–210	30	7–160
Hungary	10.05	370	79–570	29	12–66	33	14–76	28	12–45
Poland [J7]	38.60	410	110–970	26	5–120	26	5–120	21	4–77
Romania [I12]	22.66	490	250–1 100	32	8–60	32	8–60	38	11–75
Russian Federation	148.1	520	100–1 400	19	0–67	27	1–76	30	2–79
Slovakia	5.35	520	200–1 380	32	15–130	32	12–120	38	12–80
South Europe									
Albania	3.40	360	15–1 150	23	6–96			24	4–160
Croatia	4.50	490	140–710	110	83–180	54	21–77	45	12–65
Cyprus	0.76	140	0–670			17	0–120		
Greece	10.49	360	12–1 570	25	1–240	25	1–240	21	1–190
Portugal	9.81	840	220–1 230	49	26–82	44	8–65	51	22–100
Slovenia	1.92	370	15–1 410			41	2–210	35	2–90
Spain	39.67	470	25–1 650			32	6–250	33	2–210
Median		400	140–850	35	16–110	35	17–60	30	11–64
Population-weighted average		420		33		32		45	

Table 6
External exposure rates calculated from various concentrations of terrestrial radionuclides in soil

Radio-nuclide	*Concentration in soil (Bq kg^{-1})*		*Dose coefficient [I20, S49] (nGy h^{-1} per Bq kg^{-1})*	*Absorbed dose rate in air (nGy h^{-1})*	
	Median value [a]	*Population-weighted value* [a]		*Median value*	*Population-weighted value*
^{40}K	400	420	0.0417	17	18
^{228}U series	35	33	0.462	16	15
^{232}Th series	30	45	0.604	18	27
Total				51	60

a Values from Table 5.

Table 7
External exposure rates from terrestrial gamma radiation
Data not referenced are from UNSCEAR Survey of Natural Radiation Exposures

Region / country	*Population in 1996 (10^6)*	*Absorbed dose rate in air (nGy h^{-1})*				*Ratio indoors to outdoors*
		Outdoors		*Indoors*		
		Average	*Range*	*Average*	*Range*	
Africa						
Algeria [B4]	28.78	70	20–133		14–2 100	
Egypt [H9, I13]	63.27	32	8–93			
Namibia [S12]	1.58					
Sudan	27.29	53	26–690			
North America						
Canada [G3, T14]	29.68	63	43–101			
Cuba [S13]	11.02	42	26–53			
Mexico [C8]	92.72	78	42–140			
United States [M8, O5]	269.4	47	14–118	38	12–160	0.8
South America						
Chile [S14]	14.42	51	21–83	61	25–105	1.2
Paraguay	4.96	46	38–53			
East Asia						
Brunei [L20]	0.30	33	3–70			
China [N3]	1232	62	2–340	99	11–420	1.6
– Taiwan Province [C11]	20	57	17–87			
– Hong Kong SAR [W12]	6.19	87	51–120	200	140–270	2.3
India [N11]	944.6	56	20–1 100			
Indonesia	200.45	55	47–63			
Japan [A7, A8]	125.4	53	21–77	53	21–77	1.0
Kazakstan	16.82	63	10–250	70	20–100	1.1
Korea, Rep. of	45.31	79	18–200			
Malaysia	20.58	92	55–130	96	65–130	1.0
Philippines [D3]	69.28	56	31–120			
Thailand	58.70	77	2–100	48	2–22	0.6
West Asia						
Iran (Islamic Rep. of)	69.98	71	36–130	115	70–165	1.6
Syrian Arab Republic	14.57	59	52–67			
North Europe						
Denmark [N5, S15]	5.24	52	35–70	54	19–260	1.0
Estonia	1.47	59	14–230			
Finland [A9]	5.13	71	45–139	73	22–184	1.0
Iceland [E4]	0.27	28	11–83	23	14–32	0.8
Lithuania	3.73	58	36–85	85	34–195	1.5
Norway [S16, S17]	4.35	73	20–1 200	79	20–1 250	1.1
Sweden [M9]	8.82	56	40–500	110	20–2 000	2.0
West Europe						
Austria [T5]	8.11	43	20–150			
Belgium [D4, S18]	10.16	43	13–80	60	32–90	1.4
France [M10, R3]	58.33	68	10–250	75		1.1
Germany [B5, W11]	81.92	50	4–350	70	13–290	1.4
Ireland [M11, M12]	3.55	42	1–180	62	10–140	1.5
Luxembourg	0.41	49	14–73			
Netherlands [J2, V1]	15.58	32	10–60	64	30–100	2.0
Switzerland	7.22	45	15–120	62	20–200	1.4
United Kingdom [G4, W5]	58.14	34	8–89	60		1.8
East Europe						
Bulgaria [V2]	8.47	70	48–96	75	57–93	1.1
Hungary [N14, N15]	10.05	61	15–130	95	11–236	1.6
Poland [B10, M3]	38.60	45	18–97	67	28–167	1.5
Romania [I12]	22.66	59	21–122	83	30–170	1.4
Russian Federation	148.1	65	12–102	74	24–147	1.1
Slovakia	5.35	67	24–154	79	36–180	1.2
South Europe						
Albania	3.40	71	20–350	100	20–300	1.4
Cyprus	0.76	18	9–52			
Greece	10.49	56	30–109	67	36–131	1.2

Table 7 (continued)

Region / country	*Population in 1996 (10^6)*	*Absorbed dose rate in air (nGy h^{-1})*				*Ratio indoors to outdoors*
		Outdoors		*Indoors*		
		Average	*Range*	*Average*	*Range*	
South Europe						
Italy [B6, C12]	57.23	74	3–228	105	0–700	1.4
Portugal [A10]	9.81	84	4–230	101	4–280	1.2
Slovenia	1.92	56	4–147	75	40–250	1.3
Spain [Q1, Q2]	39.67	76	40–120	110	57–180	1.4
Oceania						
Australia [C13, L7]	18.06	93		103		1.1
New Zealand [R4]	3.6			20	1–73	
Median		57	18–93	75	20–200	1.3 (0.6–2.3)
Population-weighted average		59		84		1.4

Table 8
Outdoor absorbed dose rates in air inferred from concentrations of radionuclides in soil compared with direct measurements

Country	*Absorbed dose rate in air (nGy h^{-1})*		
	From soil concentrations	*From direct measurements*	*Ratio soil/measurements*
Luxembourg	72	49	1.5
Ireland	58	42	1.4
Sweden	77	56	1.4
India	69	56	1.2
China (Hong Kong SAR)	107	87	1.2
Norway	86	73	1.2
United States	55	47	1.2
Switzerland	49	45	1.1
Kazakstan	65	63	1.0
Belgium	44	43	1.0
Portugal	86	84	1.0
Malaysia	93	92	1.0
Egypt	32	32	1.0
Slovenia	56	56	1.0
Romania	58	59	1.0
China	58	62	0.9
Poland	42	45	0.9
Estonia	54	59	0.9
Slovakia	60	67	0.9
Japan	45	53	0.8
Lithuania	48	58	0.8
Thailand	62	77	0.8
Russian Federation	52	65	0.8
Bulgaria	56	70	0.8
Hungary	48	61	0.8
Algeria	54	70	0.8
Iran (Islamic Rep. of)	53	71	0.7
Denmark	39	52	0.7
Spain	54	76	0.7
Greece	39	56	0.7
Albania	40	71	0.6
Syrian Arab Republic	33	59	0.6

Table 9
Distribution of population with respect to the outdoor absorbed dose rate in air from terrestrial gamma radiation

Region / country	*Population (10^3) residing in areas with various levels of outdoor absorbed dose rate in air*											
	< 20 nGy h^{-1}	*20-29 nGy h^{-1}*	*30-39 nGy h^{-1}*	*40-49 nGy h^{-1}*	*50-59 nGy h^{-1}*	*60-69 nGy h^{-1}*	*70-79 nGy h^{-1}*	*80-89 nGy h^{-1}*	*90-99 nGy h^{-1}*	*100-199 nGy h^{-1}*	*200-299 nGy h^{-1}*	*>300 nGy h^{-1}*
East Asia												
Japan		9 619	26 463	20 561	23 382	39 546	5 193					
Korea	1 760	3 096	9 605	4 097	2 220	1 724	4 421	4 421	2 211	11 053		
Malaysia					984	213	1 214	2 498	8 487	6 248		
West Asia												
Iran (Islamic Rep. of)			3 580	1 260	4 896	29 400	4 810	13 080	3 660	3 200		
North Europe												
Denmark		250	2 100	2 200	600	50						
Estonia	6	5	25	149	314	367	592	9				
Finland					913	1 131	2 606	172	325			
Lithuania			138	967	414	1 381	553	276				
West Europe												
Belgium	300	2 200	2 400	2 600	2 500	200	20					
Germany	700	8 600	10 000	20 900	28 000	9 600	1 500	800	700	300		
Italy	125		275	5 300	28 075	8 575	1 975	150	3 100	6 400	3 300	
Luxembourg	29	13	52	230	82	4						
Netherlands	3 459	5 484	2 353	2 976	1 262	47						
Switzerland	60	631	1 131	3 983	584	74	161	74	64	98		
United Kingdom	6 000	12 000	30 000	6 000								
East Europe												
Bulgaria				186	392	5 212	1 239	234	1 614			
Hungary	163	479	836	1 071	1 316	3 488	1 163	765	367	530		17
Poland	150	2 915	12 014	12 268	7 163	2 637	622	213	136			
Romania		295	1 407	4 177	6 447	5 130	3 904	726	568	45		
Russian Federation	450		460	7 150	22 800	84 470	5 730	17 800	5 330	3 910		
Slovakia		22	192	721	1 364	1 292	868	498	243	85		
South Europe												
Albania	0	50	50	100	100	500	2 000	300	200	100	50	50
Greece			1 160	5 605	1 067	1 250	572	147	225	231		
Portugal	333	444	1 814	606	1 325	653	313	582	417	2 352	594	
Spain			1 115	5 490	5 082	10 129	2 903	1 977	2 447	8 152		
Total	13 535	46 103	107 170	108 597	141 282	207 073	42 359	44 722	30 094	42 704	3 944	67
Fraction of total	0.017	0.059	0.14	0.14	0.18	0.26	0.054	0.057	0.038	0.054	0.005	0.00009
Cumulative total	13 535	59 638	166 808	275 405	416 687	623 760	666 119	710 841	740 935	783 639	787 583	787 650
Cumulative fraction	0.017	0.08	0.21	0.35	0.53	0.79	0.85	0.90	0.94	0.995	0.9999	1.000

Table 10
Distribution of population with respect to the average outdoor absorbed dose rate in air from terrestrial gamma radiation

Region / country	*Base population* (10^6)	*Average outdoor dose rate* (nGy h^{-1})	*Fraction of population with respect to decades of outdoor absorbed dose rate in air* [a]												
			-6	*-5*	*-4*	*-3*	*-2*	*-1*	*0*	*1*	*2*	*3*	*4*	*5*	*6*
East Asia															
Japan	124.8	53				0.08	0.21	0.16	0.19	0.32	0.04				
Korea	44.6	79	0.04	0.07	0.22	0.09	0.05	0.04	0.10	0.10	0.05	0.25			
Malaysia	19.6	92			0.05	0.01	0.06	0.13	0.43	0.32					
West Asia															
Iran (Islamic Rep.)	63.9	71			0.065	0.02	0.08	0.46	0.08	0.20	0.057	0.05			
North Europe															
Denmark	5.2	52					0.05	0.40	0.42	0.12	0.01				
Estonia	1.5	59		0.004	0.003	0.02	0.10	0.21	0.25	0.40	0.006				
Finland	5.1	71					0.18	0.22	0.51	0.03	0.06				
Lithuania	3.7	61				0.04	0.26	0.11	0.37	0.15	0.07				
West Europe															
Belgium	10.2	43				0.03	0.22	0.23	0.25	0.24	0.02	0.002			
Germany	81.1	50			0.01	0.12	0.12	0.25	0.34	0.12	0.02	0.01	0.01		
Italy	57.3	74	0.002		0.005	0.09	0.49	0.15	0.03	0.003	0.05	0.11	0.06		
Luxembourg	0.4	43				0.07	0.03	0.13	0.56	0.20	0.01				
Netherlands	15.6	32					0.22	0.35	0.15	0.19	0.08	0.003			
Switzerland	6.9	45				0.009	0.09	0.16	0.58	0.09	0.01	0.02	0.01	0.009	0.01
United Kingdom	54.0	34					0.11	0.22	0.56	0.11					
East Europe															
Bulgaria	8.9	70				0.02	0.04	0.59	0.14	0.03	0.18				
Hungary	10.2	61		0.02	0.05	0.08	0.11	0.13	0.34	0.11	0.08	0.04	0.05		0.002
Poland	38.1	45				0.004	0.08	0.32	0.32	0.19	0.07	0.02	0.006	0.004	
Romania	22.7	59				0.01	0.06	0.18	0.28	0.23	0.17	0.03	0.03	0.002	
Russian Fed.	148.1	65		0.003		0.003	0.05	0.15	0.57	0.04	0.12	0.04	0.03		
Slovakia	5.3	67			0.004	0.04	0.14	0.26	0.24	0.16	0.09	0.05	0.02		
South Europe															
Albania	3.5	71		0.01	0.01	0.03	0.03	0.14	0.57	0.09	0.06	0.03	0.01	0.01	
Greece	10.3	56					0.11	0.55	0.10	0.12	0.06	0.01	0.02	0.02	
Portugal	9.4	84	0.05	0.19	0.06	0.14	0.07	0.03	0.06	0.04	0.25	0.06			
Spain	37.3	76			0.03	0.15	0.14	0.27	0.08	0.05	0.07	0.22			
Total population (10^6)	787.7 [b]		2.3	5.6	17.5	39.8	108	171	232	111	50.8	38.0	9.8	0.53	0.12
Fraction of total			0.003	0.007	0.022	0.051	0.14	0.22	0.29	0.14	0.064	0.048	0.012	0.0007	0.0001

a The average outdoor absorbed dose rate in air in the country is placed in the decade 0; e.g. for 52 nGy h^{-1} average, would indicate decade 0 is the dose interval 50-59 nGy h^{-1}, decade -1 is 40-49 nGy h^{-1}, etc.
b Total distributed population within ranges indicated is 787.3 10^6.

Table 11
Areas of high natural radiation background

Country	*Area*	*Characteristics of area*	*Approximate population*	*Absorbed dose rate in air* [a] *(nGy h^{-1})*	*Ref.*
Brazil	Guarapari	Monazite sands; coastal areas	73 000	90–170 (streets) 90–90 000 (beaches)	[P4, V5]
	Mineas Gerais and Goias			110–1 300	[A17, P4]
	Pocos de Caldas Araxá	Volcanic intrusives	350	340 average 2 800 average	[V5]
China	Yangjiang Quangdong	Monazite particles	80 000	370 average	[W14]
Egypt	Nile delta	Monazite sands		20–400	[E3]
France	Central region Southwest	Granitic, schistous, sandstone area Uranium minerals	7 000 000	20–400 10–10 000	[J3] [D10]
India	Kerala and Madras	Monazite sands, coastal areas 200 km long, 0.5 km wide	100 000	200–4 000 1 800 average	[S19, S20]
	Ganges delta			260–440	[M13]
Iran (Islamic Rep. of)	Ramsar Mahallat	Spring waters	2 000	70–17 000 800–4 000	[S21] [S58]
Italy	Lazio Campania Orvieto town South Toscana	Volcanic soil	5 100 000 5 600 000 21 000 ~100 000	180 average 200 average 560 average 150–200	[C12] [C12] [C20] [B21]
Niue Island	Pacific	Volcanic soil	4 500	1 100 maximum	[M14]
Switzerland	Tessin, Alps, Jura	Gneiss, verucano, ^{226}Ra in karst soils	300 000	100–200	[S51]

a Includes cosmic and terrestrial radiation.

Table 12
Distribution of population with respect to the indoor absorbed dose rate in air from terrestrial gamma radiation

Region / country	*Population (10^3) residing in areas with various levels of indoor absorbed dose rate in air*											
	< 20 nGy h^{-1}	*20-29 nGy h^{-1}*	*30-39 nGy h^{-1}*	*40-49 nGy h^{-1}*	*50-59 nGy h^{-1}*	*60-69 nGy h^{-1}*	*70-79 nGy h^{-1}*	*80-89 nGy h^{-1}*	*90-99 nGy h^{-1}*	*100-199 nGy h^{-1}*	*200-299 nGy h^{-1}*	*>300 nGy h^{-1}*
North Europe												
Denmark		80	300	600	1 100	1 300	1 000	600	200	50	10	
Finland		144	633	779	636	398	474	491	470	1 122		
Lithuania			23	145	239	633	746	798	338	807		
West Europe												
Belgium			600	2 000	2 500	2 500	2 000	620				
East Europe												
Bulgaria					270	3 362	2 370	2 572	201	102		
Hungary	245	581	306	245	357	696	696	903	1 150	4 988	17	16
Romania			23	272	1 498	2 293	5 538	7 038	5 176	794	68	
Russian Federation		460	7 670	20 970	21 020	24 660	12 810	4 860	38 670	16 980		
South Europe												
Greece			329	900	5 536	1 043	1 135	417	293	603		
Italy	800	2 175	4 225	5 400	4 400	3 975	4 850	8 500	6 800	8 875	4 025	3 250
Spain					1 115	5 490	1 285	8 908	4 015	15 584	906	
Total	1 045	3 440	14 109	31 311	38 671	46 350	32 904	35 707	57 313	49 905	5 026	3 266
Fraction of total	0.003	0.011	0.044	0.10	0.12	0.15	0.10	0.11	0.18	0.16	0.016	0.010
Cumulative total	1 045	4 485	18 594	49 905	88 576	134 927	167 831	203 537	260 851	310 755	315 781	319 047
Cumulative fraction	0.003	0.014	0.058	0.16	0.28	0.42	0.53	0.64	0.82	0.97	0.99	1.000

Table 13
Reference annual intake of air, food, and water
[I7, W1]

Intake	*Breathing rate (m^3 a^{-1})*		
	Infants (1 year)	*Children (10 years)*	*Adults*
Air	1 900	5 600	7 300
Intake	*Food consumption rate (kg a^{-1})*		
	Infants	*Children*	*Adults*
Milk products	120	110	105
Meat products	15	35	50
Grain products	45	90	140
Leafy vegetables	20	40	60
Roots and fruits	60	110	170
Fish products	5	10	15
Water and beverages	150	350	500

Table 14
Concentrations of uranium and thorium series radionuclides in air

Region / country	*Concentration (µBq m^{-3})*									*Ref.*
	^{238}U	^{230}Th	^{226}Ra	^{210}Pb	^{210}Po	^{232}Th	^{228}Ra	^{228}Th	^{235}U	
North America United States	0.9–5	0.6	0.6	100-1 000	10-40	0.4		1.0	0.04	[F3, L8, M15, P5, W6]
Europe Germany Netherlands Norway Poland Switzerland	0.3–1.7 0.02–0.06 1–18	0.3–1.7 0.02–0.07	1.2–3.3 0.8–32	28–2 250 410 <40–710 200-2 000	12-80	0.2–0.9 0.01–0.07	<0.3-1.5			[H31, K4, K10] [N21] [K4] [K5] [S51]
Reference value	1	0.5	1 (0.5) [a]	500	50	0.5 (1)[a]	1	1	0.05	[U3]

a Revised value; previous value [U3] in parentheses.

Table 15
Concentrations of uranium and thorium series radionuclides in foods and drinking water

Region / country	*Concentration (mBq kg^{-1})*									*Ref.*
	^{238}U	^{230}Th	^{226}Ra	^{210}Pb	^{210}Po	^{232}Th	^{228}Ra	^{228}Th	^{235}U	
Milk products										
North America										[F3, M16]
United States	0.7	0.4	5.7	11		0.27			0.05	
Asia										
China	13		6	16	13	1.2	21		0.6	[Z1]
India	17				15					[D6, K6]
Japan	0.55		12			0.29				[S22]
Europe										
Italy			3–19							[M17]
Germany			2–130	5–280	2–80					[B3, J4, M18]
Poland	2.6	1.2	10	18	16	1.2				[P3, P7]
Romania			0.9–44	11–15	13–140					[B20,R20]
U.K.	0.1–4.9		<0.4–200	35–88	20–220			56		[B2]
Reference value	1	0.5	5	15 (40) [a]	15 (60)	0.3	5	0.3	0.05	
Meat products										
North America										
United States	0.8–2.3	0.5–3	20	18		0.3–2			0.02	[F3,M16]
Asia										
China	10		41	140	120	4.3	120		0.5	[Z1]
India					440					[K6]
Japan	13		36			2.3				[S22]
Europe										
Germany	1–20		30–220	100–1 000	37-4 000					[B3, G5,M18]
Poland	1.6–5.6	0.7–3.0	11–19	98–105	99–102	0.5–3.6				[P3, P7]
Romania			2–30	15–19	38–110					[B20,R20]
U.K.	4.9		2.6–74	40-3 700	62-67 000			22–93		[B2]
Reference value	2	2	15	80	60	1	10	1	0.05	
Grain products										
North America										
United States	3–23	0.9–10	7–100	33–81		0.1–2.8			0.1–1.3	[F3,M16]
Asia										
China	9.8		17	34	42	13	38		0.5	[Z1]
India	7.4–67				15–120					[D6, K6]
Japan	1.2		14			1.2				[S22]
Europe										
Germany	20–400		20-2 900	40-4 000	37–1 900					[B3, G5]
Poland	4.7–11	1.4–17	80–110	110–160	90–140	2.0–21				[P3, P7]
Romania	6.1–85		30–90	49–59	20–360	1.6–33				[B20,R20]
U.K.	6.2–35		0.7-5 200	56–120	27–260	12		180-2300		[B2]
Reference value	20	10	80	50 (100)	60 (100)	3	60	3	1	
Leafy vegetables										
North America										
United States	24	20	56	41		18			1.2	[F3,M16]
Asia										
China	16		75	360	430	23	220		0.7	[Z1]
India	61–72				320					[D6, K6]

Table 15 (continued)

Region / country	*Concentration (mBq kg^{-1})*									*Ref.*
	^{238}U	^{230}Th	^{226}Ra	^{210}Pb	^{210}Po	^{232}Th	^{228}Ra	^{228}Th	^{235}U	
Europe Germany Italy Poland U.K.	 6–2 200 14–15 9.8–400	 6–9 80–380	 6–1 150 27–44 37–43 2.2–170	 4–4 100 43–51 16-3 300	 4–7 400 40–67 37-3 300	 4–7				[B3, G5,M18] [D9] [P3, P7] [B2]
Reference value	20	20	50	80 (30)	100 (30)	15	40	15	1	
Root vegetables and fruits										
North America United States	 0.9–7.7	 0.2–1.1	 7–47	 8–150		 0.08–1.4			 0.1	 [F3,M16]
Asia China India Japan	 13 0.4–77 26		 63 11	 27	 29 16–140	 4.7 2.3	 110		 0.6	 [Z1] [D6, K6] [S22]
Europe Germany Italy Poland Romania U.K.	 10-2 900 0.9–10 6–120 6	 0.7–7.5	 5–9 400 14–25 11–215 9–190 9.0–41	 20-4 900 24–93 19–44 18–76	 22–5 200 28–210 12–140	 0.7–7.1 0.4–2.1		 22		 [B3, G5,M18] [D9] [P3, P7] [B20,R20] [B2]
Reference value	3	0.5	30	30 (25)	40 (30)	0.5	20	0.5	0.1	
Fish products										
North America United States	 13-1 900	 1.2–29	 30–59	 14-1 800	 150-55 000	 1.2–30			 0.4-90	 [F3, M16, S23]
Asia China	 12		 39	 3 500	 4 900	 1.3	 320		 0.5	 [Z1]
Europe France Germany Poland Portugal U.K.	 2.5		 37 100-7 400 28–43 8.5-2 100	 20-4 400 81–93 180-4 800	 50-5 200 3 100-3 800 80-120 000 60-53 000			 56–700		 [P6] [G5,M18] [P7] [C14] [B2]
Reference value	30	10	100	200	2 000	10		100		
Drinking water										
North America United States	 0.3–77	 0.1	 0.4–1.8	 0.1–1.5		 0.05	 0–0.5		 0.04	[C15, F3, H11, M20]
Asia China India	 0.1–700 0.09–1.5		 0.2–120			 0.04–12				 [N3] [D6]
Europe Finland France Germany Italy Poland Romania Switzerland Spain U.K.	 0.5– 150 000 4.4–930 0.4–600 0.5–130 7.3 0.4–37 0–1 000 3.7–4.4	 1.4	 10– 49 000 7–700 1–1 800 0.2–1200 1.7–4.5 0.7–21 0–1500 <20-4 000 0–180	 0.2– 21 000 0.2–200 1.6 7–44 40–200	 0.2–7 600 0.1–200 0.5 7–44	 0–4.2 0.06 0.04–9.3	 18-570 0–200	 	 0–50	 [A16,S11] [D8, P6] [B3, G5, G6] [S55] [P3, P7] [B20,R20] [S51] [S24] [B2]
Reference value	1	0.1	0.5	10	5	0.05	0.5	0.05	0.04	

a Revised value with previous value [U3] (if different) in parentheses.

Table 16
Annual intake of uranium and thorium series radionuclides in diet

Region / country	*Annual intake (Bq)*									*Ref.*
	^{238}U	^{230}Th	^{226}Ra	^{210}Pb	^{210}Po	^{232}Th	^{228}Ra	^{228}Th	^{235}U	
North America										
Puerto Rico			9.1							[H13]
United States	5.5–6.2	2.2–3.7	10–24	16–23	22	1.1–2.2	13–16	7.3–8.0		[B8, F3, F5, H12, L9, M23, M24, P8, S31, S33, W6]
South America										
Argentina			9.5		18					[B7, U8]
Brazil			40				40			[L10, P9]
Asia										
China	57		12–32	75–110	68–130	9.3	66		2.6	[L16,Y5,Y6, Z1]
India	2.9		8.8	46	20	3.3	47			[C16, D5, L11, S41]
Japan	3.2–6.6	0.6	9–15	73–80	220	0.6–0.8				[K7, N13, S22, S27, S42, S45]
Europe										
Belgium			16							[S28]
Bulgaria				22–28						[K8]
Czech Rep.			40							[T6]
France	4.4		14–19	18						[G7, S32, U8]
Germany	11	3.4	40	62		2.2	17	17		[F4, G8, M22]
Italy			11–19	40	40					[C17, D9, M21]
Netherlands			27							[S28]
Poland	6.4	2.1	19–20	45	44	1.2				[P3, P7]
Romania	5.8		19	57	51	2.2		2.2		[I12]
Russian Fed.	16			55–84	40–55					[D7, L12]
U.K.	4.4		11–16	16–30	28–44					[C18, H14, H15, S29, S30]
Reference value [a]	5.7	3.0	22	30	58	1.7	15	3.0	0.2	

a Intake by adults; consumption rates from Table 13 and reference concentrations in foods and water from Table 15.

Table 17
Annual effective dose from inhalation of uranium and thorium series radionuclides

Radio-nuclide	*Concentration in air ($\mu Bq\ m^{-3}$)*	*Effective dose coefficient [I9] ($\mu Sv\ Bq^{-1}$)*			*Committed effective dose [a, b] (μSv)*			
		Infants	*Children*	*Adults*	*Infants*	*Children*	*Adults*	*Age-weighted*
^{238}U	1	9.4	4	2.9	0.018	0.022	0.021	0.021
^{234}U	1	11	4.8	3.5	0.021	0.027	0.026	0.026
^{230}Th	0.5	35	16	14	0.033	0.045	0.051	0.048
^{226}Ra	1	11	4.9	3.5	0.021	0.027	0.026	0.026
^{210}Pb	500	3.7	1.5	1.1	3.5	4.2	4.0	4.0
^{210}Po	50	11	4.6	3.3	1.0	1.3	1.2	1.2
^{232}Th	0.5	50	26	25	0.048	0.073	0.091	0.084
^{228}Ra	1	10	4.6	2.6	0.019	0.026	0.019	0.021
^{228}Th	1	130	55	40	0.25	0.31	0.29	0.29
^{235}U	0.05	10	4.3	3.1	0.001	0.001	0.001	0.001
Total					5.0	6.0	5.8	5.8

a Assumed breathing rates: infants 1,900 $m^3\ a^{-1}$, children 5,600 $m^3\ a^{-1}$, adults 7,300 $m^3\ a^{-1}$.
b Committed effective dose from the annual intake. Age distribution for weighted values: infants 0.05, children 0.3, adults 0.65.

Table 18
Annual intake and effective dose from ingestion of uranium and thorium series radionuclides

Radio-nuclide	*Activity intake [a] (Bq)*			*Effective dose coefficient [I2, I21] ($\mu Sv\ Bq^{-1}$)*			*Committed effective dose [b] (μSv)*			
	Infants	*Children*	*Adults*	*Infants*	*Children*	*Adults*	*Infants*	*Children*	*Adults*	*Age-weighted*
^{238}U	1.9	3.8	5.7	0.12	0.068	0.045	0.23	0.26	0.25	0.25
^{234}U	1.9	3.8	5.7	0.13	0.074	0.049	0.25	0.28	0.28	0.28
^{230}Th	1.0	2.0	3.0	0.41	0.24	0.21	0.42	0.48	0.64	0.58
^{226}Ra	7.8	15	22	0.96	0.80	0.28	7.5	12	6.3	8.0
^{210}Pb	11	21	30	3.6	1.9	0.69	40	40	21	28
^{210}Po	21	39	58	8.8	2.6	1.2	180	100	70	85
^{232}Th	0.6	1.1	1.7	0.45	0.29	0.23	0.26	0.32	0.38	0.36
^{228}Ra	5.5	10	15	5.7	3.9	0.69	31	40	11	21
^{228}Th	1.0	2.0	3.0	0.37	0.15	0.072	0.38	0.30	0.22	0.25
^{235}U	0.1	0.2	0.2	0.13	0.071	0.047	0.011	0.012	0.012	0.011
Total							260	200	110	140

a Consumption rates from Table 13 and concentrations in foods and water (reference values) from Table 15.
b Committed effective dose from the annual intake. Age distribution for weighted values: infants 0.05, children 0.3, adults 0.65.

Table 19
Uranium and thorium series radionuclides in human tissues

Region / country	*Concentration (mBq kg^{-1})*					*Ref.*
	Lung	*Liver*	*Kidney*	*Muscle and other tissues*	*Bone* [a]	
^{238}U						
Africa Nigeria					340	[F9]
North America Canada United States	6.2–15	1.5–4.1	4.8–12		120 11–52	[F9] [F8, S44]
South America Brazil					130–150	[F9]
East Asia China India Japan Nepal	21	3.0	27 4.2	5.3	410 (94–2 600) 140 17–59 110	[L1] [G13] [I17] [F10]
Europe Austria United Kingdom Yugoslavia		3.1	62	2.4	10 150 2.7	[H20] [H15] [P14]
Russian Federation	67–84	72–140	66–68	81–95	74–120	[D7, F10, M31]
Oceania Australia					23	[F10]
Median value Range	21 (6–84)	3 (2–140)	27 (4–68)	5 (2–95)	100 (3–410)	
Reference value	20 (15) [b]	3	30 (5)	5 (2)	100 (50)	
^{230}Th						
Africa Nigeria					110	[F11]
North America Canada United States	12–31	6	6–11		41 45–130	[F11] [H23, I15, S1]
East Asia China Japan	29 19	12	1	1.4	120 (58–220) 24	[C3] [H22]
Median value Range	19 (12–29)	9 (6–12)	5 (1–11)	1	76 (24–120)	
Reference value	20	9 (7)	5 (10)	1 (0.3)	20–70 [c]	
^{226}Ra						
16 countries [d] 31 countries [e]	3.6 4.1	3.6 4.1	3.6 4.1	3.6 4.1	230 260	[F15, U7] [F16]
Reference value	4.1 (2.7)	4.1 (2.7)	4.1 (2.7)	4.1 (2.7)	260 (170)	
^{210}Pb						
Europe Finland Russian Federation	240	90 450	170 270	30 140–270	2 400 5 000	[K17] [L12]
East Asia Japan	240	560	430	30–230	2 600	[T13]
North America United States	230	340	160	140		[B22]

Table 19 (continued)

Region / country	*Concentration (mBq kg^{-1})*					*Ref.*
	Lung	*Liver*	*Kidney*	*Muscle and other tissues*	*Bone* [a]	
Median value Range	240 (230–240)	400 (90–560)	220 (160–430)	110 (30–270)	2 600 (2 400–5 000)	
Reference value	200	400 (200)	200	100 (200)	3 000	
^{210}Po						
Europe Finland Russian Federation United Kingdom	 330 200	 510 970 630	 490 760 640	 110 110–220 120	 2 200 2 400 2 200	 [K17] [L12] [H10]
East Asia Japan	370	1 700	1 200	40–310	2 600	[T13]
North America United States	190	410–540	420	130–220	2 900	[B22, H30]
Median value Range	270 (190–370)	630 (410–970)	640 (420–1 200)	120 (40–310)	2 400 (2 200–2 900)	
Reference value	200 (100)	600 (200)	600 (200)	100 (200)	2 400	
^{232}Th						
Africa Nigeria					86	[F11]
North America Canada United States	 9.3–32	 2.2–3.0	 1.9–4.1		15 21–35	[F11] [H23, I15, L15, S1, W7]
East Asia China India Japan	 38 24 22	 3.6 2.1	 6.8 1.0	 2.2 0.8	 68 (34–140) 8 11	 [C3] [J8, S41] [H22]
Europe United Kingdom Yugoslavia	 22				 62 50	 [H21] [P14]
Median value Range	22 (9–53)	3 (2–4)	3 (1–7)	1 (1–2)	38 (8–86)	
Reference value	20	3 (2)	3	1 (0.15)	6–24 [c]	
^{228}Ra						
Africa Nigeria					320	[F11]
North America Canada United States	 9–10	 2.6–3.3	 2.6–3.3		 23 39–230	 [F11] [I15, S1]
East Asia China Japan	 41 19	 3.9	 1.3	 1.5	 290 (140–570) 100	 [C3] [H22]
Median value Range	19 (9–41)	3 (3–4)	2 (1–3)	2	100 (23–320)	
Reference value	20 (15)	3 (5)	2 (10)	2 (0.5)	100 (50)	

a Assumes 5 kg dry bone yields 2.7 kg ash per skeleton.
b Revised reference value with previous value [U4] (if different) in parentheses.
c First value given is for cortical bone and the second value for trabecular bone.
d Representing 30% of the world population.
e Representing 66% of the world population.

Table 20
Dose rates to adults from ingestion of uranium and thorium radionuclides estimated from reference concentrations in tissues

Tissue	*Concentration (mBq kg^{-1})*					
	$^{238/234}U$	^{230}Th	^{226}Ra	$^{210}Pb/Po$	^{232}Th	$^{228/224}Ra$
Bone	100	30 [b]	260	2 400 [c]	9.6[b]	100
Lung	20	20	4.1	200	20	20
Kidney	30	5	4.1	600	3	2
Liver	3	9	4.1	600	3	3
Other [a]	5	1	4.1	100	1	2
	Absorbed dose rate per unit concentration (μGy a^{-1} per mBq kg^{-1}) [U4]					
	$^{238/234}U$	^{230}Th	^{226}Ra [d]	$^{210}Pb/Po$	^{232}Th	$^{228/224}Ra$
Soft tissues	0.046	0.024	0.063	0.027	0.020	0.16
Bone marrow	0.085	1.9	0.18	0.046	1.1	0.70
Bone lining cells [e]	0.008	0.005	0.022	0.005	0.003	0.056
	Effective dose rate (μSv a^{-1})					
	$^{238/234}U$	^{230}Th	^{226}Ra	$^{210}Pb/Po$	^{232}Th	$^{228/224}Ra$
Body [f]	7	6	7	80	4	18
Total [f]	120					
Intake [g]	0.5	0.6	6	91	0.4	11
Total [g]	110					

a Includes gonads, breast, red bone marrow, and thyroid.
b Assumes 4 kg cortical and 1 kg trabecular bone in 5 kg skeleton.
c Concentration of ^{210}Po.
d Includes dose from ^{222}Rn and its short-lived decay products; retention factor of one third.
e Referred to concentration in bone; cells located 10 μm from bone surface [H23].
f Estimated from reference concentrations in body.
g Estimated from intake of radionuclides in foods and water for adults (see Table 18).

Table 21
Parameters of the model masonry house

Parameter	*Notation*	*Value*
Dimensions and relevant parameters		
Volume		250 m^3
Surface area of floor		100 m^2
Length of floor to wall gap		40 m
Width of floor to wall gap		3 mm
Total surface area including internal walls, furniture, etc.		450 m^2
Air exchange rate		1 h^{-1}
Subsoil		
Activity concentration of ^{226}Ra	C_{Ra}	50 Bq kg^{-1}
Emanation fraction	f	0.2
Porosity	ε	0.25
Fraction of water saturation	m	0.2
Effective diffusion coefficient	D_e	2.0 10^{-6} m^2 s^{-1}
Bulk diffusion coefficient	D	5.0 10^{-7} m^2 s^{-1}
Soil density	ρ	1 600 kg m^{-3}
Permeability	k	2 10^{-11} m^2
Aggregate layer thickness [a]		0.15 m
Aggregate layer permeability [a]		5 10^{-9} m^2
Building elements, wall and floor		
Thickness of floor		0.1 m
Thickness of walls and ceiling		0.2 m
Activity concentration of ^{226}Ra	C_{Ra}	50 Bq kg^{-1}
Emanation fraction	f	0.1
Porosity of wall	ε	0.15
Porosity of floor		0.20
Effective diffusion coefficient of wall	D_e	7 10^{-8} m^2 s^{-1}
Effective diffusion coefficient of floor		1 10^{-7} m^2 s^{-1}
Density	ρ	1 600 kg m^{-3}

a The other specifications of the aggregate layer are similar to the subsoil specifications.

Table 22
Representative radon entry rates of the model masonry house

Source of radon		*Radon entry rate (Bq m^{-3} h^{-1})*
Building materials	Diffusion, walls and ceiling	10
	Diffusion, floor slab	1
Subjacent earth	Diffusion through the slab	10
	Diffusion through gaps	4
	Advection	20
Outdoor air	Infiltration	10
Water supply	De-emanation	1
Natural gas	Consumption	0.3
Total		56

Table 23
Representative radon entry rates in low-rise residential houses in Finland compared to the model masonry house

Source of radon	*Mechanism*	*Radon entry rate (Bq m^{-3} h^{-1})* [a]		
		Wooden house [b]	*Masonry house* [c]	*Model masonry house* [d]
Building elements				
Walls and ceiling	Diffusion	2 (3)	16 (18)	10 (18)
Floor slab	Diffusion			1 (2)
Subjacent earth				
Through gaps	Diffusion			4(7)
	Advection	60 (86)	66 (73)	20 (35)
Through slab	Diffusion	4 (6)	4 (4)	10 (18)
Outdoor air	Infiltration	3(4)	3 (3)	10 (18)
Water supply	De-emanation	1 (1)	1 (1)	1 (2)
Natural gas	Consumption			0.3 (–)
Total		70 (100)	90 (100)	56 (100)

a Percentage in parentheses.
b Radon concentration indoors 140 Bq m^{-3}; air exchange rate 0.5 h^{-1} [A1].
c Radon concentration indoors 180 Bq m^{-3}; air exchange rate 0.5 h^{-1} [A1].
d Radon concentration indoors 56 Bq m^{-3}; air exchange rate 1.0 h^{-1} [U3].

Table 24
Radon concentrations in dwellings determined in indoor surveys
Data not referenced are from UNSCEAR Survey of Natural Radiation Exposures

Region	*Country*	*Population in 1996 (10^6)*	*Radon concentration (Bq m^{-3})*			*Geometric standard deviation*	*Ref.*
			Arithmetic mean	*Geometric mean*	*Maximum value*		
Africa	Algeria	28.78	30		140		[C19]
	Egypt	63.27	9		24		[K12]
	Ghana	17.83			340		[O6]
North America	Canada	29.68	34	14	1 720	3.6	[L13]
	United States	269.4	46	25		3.1	[M26, U14]
South America	Argentina	35.22	37	26	211	2.2	[G9]
	Chile	14.42	25		86		[S14]
	Paraguay	4.96	28		51		
East Asia	China	1232	24	20	380	2.2	[Z2]
	– Hong Kong SAR	6.19	41		140		[T8]
	India	944.6	57	42	210	2.2	[S37]
	Indonesia	200.45	12		120		
	Japan	125.4	16	13	310	1.8	[F20, S61]
	Kazakstan	16.82	10		6 000		
	Malaysia	20.58	14		20		
	Pakistan	140.0	30		83		[T9]
	Thailand	58.7	23	16	480	1.2	
West Asia	Armenia	3.64	104		216	1.3	
	Iran (Islamic Rep. of)	69.98	82		3 070		[S38]
	Kuwait	1.69	14	6	120		[B15]
	Syria	14.57	44		520		[O8]
North Europe	Denmark	5.24	53	29	600	2.2	[S15, U15]
	Estonia	1.47	120	92	1 390		[P15]
	Finland	5.13	120	84	20 000	2.1	[A13, C21]
	Lithuania	3.73	55	22	1 860		
	Norway	4.35	73	40	50 000		
	Sweden	8.82	108	56	85 000		[S25]
West Europe	Austria	8.11		15	190		[S34, S35]
	Belgium	10.16	48	38	12 000	2.0	
	France	58.33	62	41	4 690	2.7	[R5]
	Germany	81.92	50	40	>10 000	1.9	
	Ireland	3.55		37	1 700		[C22]
	Luxembourg	0.41	110	70	2 500	2.0	
	Netherlands	15.58	23	18	380	1.6	[N22, P10]
	Switzerland	7.22	70	50	10 000		[S26]
	United Kingdom	58.14	20		10 000		[W5]
Eastern Europe	Bulgaria	8.47		22	250		
	Czech Republic	10.25	140		20 000		[T7]
	Hungary	10.05	107	82	1 990	2.7	[N14]
	Poland	38.60	41	32	432	2.0	[B10]
	Romania	22.66	45		1 025		[I12]
	Slovakia	5.35	87		3 750		
South Europe	Albania	3.40	120	105	270	2.0	
	Croatia	4.50	35	32	92		
	Cyprus	0.76	7	7	78	2.6	[C6]
	Greece	10.49	73	52	490		[G10]
	Italy	57.23	75	57	1 040	2.0	[B9]
	Portugal	9.81	62	45	2 700	2.2	[F7]
	Slovenia	1.92	87	60	1 330	2.2	[K15]
	Spain	39.67	86	42	15 400	3.7	
Oceania	Australia	18.06	11	8	420	2.1	[L7]
	New Zealand	3.60	20	18	90		[R4]
Median			46	37	480	2.2	
Population-weighted average			39	30	1 200	2.3	

Table 25
Thoron concentrations in outdoor and indoor air

Region / country or territory	*Equilibrium equivalent concentration [a] ($Bq\ m^{-3}$)*		*$^{220}Rn/^{222}Rn$ EEC ratio*		*Ref.*
	Outdoors	*Indoors*	*Outdoors*	*Indoors*	
North America					
United States		0.5 (0.03–4.7)		0.04	[T11]
	0.09 (0.03–0.3)	0.2 (0.1–0.3)			[H36]
East Asia					
China	0.4	0.8	0.05	0.07	[P12]
Hong Kong SAR	0.3 (0.1–0.5)	0.8 (0.4–1.2)	0.04	0.06	[T10]
Japan		0.6 (0.4–0.9) [b]		0.1	[G12, G23]
		0.5 (0.1–1.0) [b]			[Y8]
		0.2 (0.1–0.6) [b]		0.03	[Z6]
		3.2 (1.0–6.0) [c]		0.4	[G12, G23]
		2.7 (0.2–8.2) [c]			[Y8]
		1.7 (0.3–5.3) [c]		0.2	[Z6]
	0.09 (0.03–0.12)	0.7 (0.04–2.1) [d]			[Y8]
		1.5 (1.4–1.6) [d]			[G23]
Malaysia	0.5 (0.3–1.8)	1.1 (0.4–2.5)	0.08	0.08	[e]
North Europe					
Norway		0.7 (0.07–1.1)		0.04	[S43]
Sweden		0.3 (0.1–0.6)		0.01	[M29]
West Europe					
France		0.8 (0.6–13.3)		0.03	[R10]
United Kingdom		0.3 (0.07–1.1)		0.02	[C26]
Central Europe					
Germany		0.5 (0.1–1.0)			[P13]
Rep. of Moldova	0.2	1.0 (0.1–6.4)	0.04	0.05	[I16]
Romania	0.3 (0.1–0.6)	1.1 (0.1–6.4)	0.05	0.04	[I12, M30]
East Europe					
Russian Federation		1.1–7.1		0.09 (0.02–0.24)	[Z4]
South Europe					
Italy		12 (0.5–76)		0.11 (0.01–0.38)	[B14, S7, S9]
Slovenia	0.12 (0.05–0.37)		0.013		[K3]
Range	0.09–0.5	0.2–12	0.01–0.08	0.01–0.5	

a Range in parentheses.
b Concrete dwellings.
c Wood frame and mud dwellings.
d New materials, e.g. mortar wallboard.
e Response to UNSCEAR Survey of Natural Radiation Exposures.

Table 26
Principal dosimetric assessments of lung dose from deposited radon decay products

Year	*Investigator*	*Parameter values*		*Target region*	*Model type*	*Dose factor* [a] *[nGy (Bq h m^{-3})$^{-1}$]*
		Unattached fraction	*Breathing rate (m^3 h^{-1})*			
1956	Chamberlain, Dyson [C9]	0.09	1.2	Average in 45 µm epithelium	Cast of trachea and bronchi	11
1959	ICRP [I19]	0.1	1.2	Mean TB region	Deposition retention assumptions	6.7
1964	Jacobi [J10]	0.25		Basal cells (30 µm)	Findeisen/Landahl 6-region anatomical model	24
1964	Altshuler et al. [A6]	0.085	0.9	Basal cells (22 µm)	Findeisen/Landahl 6-region anatomical model	32
1967	Haque, Collinson [H24]	0.35		Basal cells (30 µm)	Weibel dichotomous airway model	71
1972	Harley, Pasternack [H25]	0.04	0.9	Basal cells (22µm)	Weibel dichotomous airway model	5.7
1980	Jacobi, Eisfeld [J5]	0.1	1.2	Mean epithelium	Weibel dichotomous airway model, correction for upper airway turbulent diffusion [M19]	8.9
1980	James et al. [J6]	0.1	1.2	Mean epithelium	Yeh-Shum anatomical model [Y4]	14
1982	Harley, Pasternack [H26]	0.07	1.1	Basal cells (22 µm)	Weibel dichotomous airway model, correction for upper airway turbulent diffusion [M19]	6.4
1982	Hoffman [H27]	0.2	0.9	Mean epithelium	Weibel dichotomous airway model, correction for upper airway turbulent diffusion [M19]]	11
1991	National Research Council [N17]	0.16	1.2	Basal cells (35–50 µm)	Yeh-Shum anatomical model [Y4], correction for upper airway turbulent diffusion	21
1996	Harley et al. [H8]	0.1	1.2	Basal cells (27 µm)	Nikiforov et al. [N9] anatomical model, airway deposition from empirical data from human airway casts	9
1998	Marsh, Birchall [M25]	0.08	0.8	Bronchial cells Basal (35–50 µm) Secretary (10–40 µm) Bronchiolar cells Secretary (4–12 µm)	ICRP lung model [I7]	 8.5 19 14

a Per unit ^{222}Rn concentration (EEC). WLM converted to Bq h m^{-3} with 0.27 10^{-3} WL (Bq m^{-3})$^{-1}$ and 170 h per working month.

Table 27
Typical concentrations of radionuclides in raw and produced materials and in wastes of the mineral processing industry

Material	*Typical concentration in ore / raw material (kBq kg^{-1})*		*Typical concentration in product or tailings / wastes (kBq kg^{-1})*	
	^{238}U-series	*^{232}Th-series*	*^{238}U-series*	*^{232}Th-series*
Phosphate industry				
Phosphate Artificial fertilizer	0.2–1.5 1.5 (Florida ore) 0.03 (Kovdor ore) 0.11 (Palfos ore) 0.3–3 0.2–1 (^{226}Ra and ^{210}Pb) 2.2 (TSP)	0.02 (Florida ore) 0.008–0.04 0.005 (TSP)	0.9–1.3 [a] 100 (^{210}Po) 600 (^{210}Pb) in calcinate 1 (Phosphorus slag)	0.02 (Phosphorus slag)
Rare earths, thorium compounds				
Monazite	6–40	4% (by weight) 8–300	450 [b]	3000 [b]
Oil and gas extraction				
Natural gas Oil	0.34 kBq m^{-3} (^{222}Rn)		(Scale) 1–1 000 (scale) 8–42 kBq m^{-3} (production water)	
Metal ores				
Iron ore Cassiterite Pyrochlore	 1 6–10	 0.3 7–80	0.1–0.3 (coal tar) 0.15 (blast furnace slag) / zinc-rich filtercake 1 (slag)	0.15 (blast furnace slag) 4 (slag)
Coal tar treatment				
Coal tar	0.1–0.3 (^{210}Po and ^{210}Pb)		0.2–0.6 (electrode pitch)	
Cokes and electric power production				
Coal	0.01–0.025	0.01–0.025	0.02–0.04 (cokes) 0.1–0.3 (coal tar) 0.2 (fly and bottom ash) 0.4 (fly dust)	0.2 (fly dust)
Cement industry				
Marl Schist Portland clinker	0.022 0.04 0.08	0.003 0.056 0.05	0.05–0.11 (cement) 0.02 (silex)	0.03–0.1 (cement) 0.003 (silex)
Mineral sands handling				
Zirconium sand Bauxite Ilmenite Rutile	0.2–74 0.4–0.6 2.3 (1.5 : ^{238}U) 3.8	0.4–40 0.3–0.4 1.2 0.56	Rutile	
Titanium pigment production				
Ilmenite Titanium ore	2.3 (1.5 : ^{238}U) 0.07–9	1.2 0.07–9	400 [c] 0.15 (VBM) 2.3 (filtercake) 0.03 (water)	up to 1 500 (scale) 0.13 (VBM) 2.6 (filtercake) 0.01 (water)

a Phosphogypsum, Central Florida ore.
b ^{226}Ra in sulphate precipitate.
c ^{226}Ra precipitate.

Table 28
Release of radionuclides from typical installations of mineral processing industries
[L18]

Industry	*Ore throughput (kt a^{-1})*	*Releases to atmosphere (GBq a^{-1})*							*Releases to water (GBq a^{-1})*						
		^{238}U	^{228}Th	^{226}Ra	^{222}Rn	^{210}Pb	^{210}Po	^{40}K	^{238}U	^{228}Th	^{226}Ra	^{222}Rn	^{210}Pb	^{210}Po	^{40}K
Elementary phosphorus	570				563	66	490		-	-	-	-	24	166	-
– Transport		0.06	0.001	0.06	0.03	0.06	0.06	0.004	0.18	0.002	0.18	0.18	0.18	0.18	0.013
Phosphoric acid	700	0.07	0.002	0.09	820	0.08	0.14	0.008	336	8	737	-	654	997	79
Fertilizer plant	375				221	0.044	0.034		-	-	-	-	0.054	0.057	-
– Transport		0.02	0.0001	0.02	0.02	0.02	0.02	0.001	0.07	0.0004	0.07	0.07	0.07	0.06	0.002
Iron and steel production	7 500				180	55	90		-	-	-	-	0.51	8	-
– Transport		0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.03	0.03	0.03	0.03	0.04	0.04	0.04
Coal tar treatment	120					~0	~0		-	-	-	-	-	-	-
Coal-fired power plant (600 MW e)	1 350	0.16	0.08	0.11	34	0.4	0.8	0.27	-	-	-	-	-	-	-
– Transport		0.004	0.004	0.004	0.004	0.004	0.004	0.012	0.011	0.011	0.011	0.011	0.011	0.011	0.036
Cokes production	885	0.013	0.009	0.013	13	0.012	0.07	0.032	-	-	-	-	0.024	0.032	-
– Transport		0.001	0.001	0.001	0.001	0.002	0.001	0.004	0.004	0.003	0.004	0.004	0.005	0.004	0.011
Cement industry	2 000	0.2	0.05	0.2	157	0.2	78	0.4	-	-	-	-	-	-	-
Ceramics	3 200	0.03		0.03	0.03	0.09	0.3	0.14	-	-	-	-	-	-	-
Mineral sands handling	183 [a]	0.97	0.12	0.73	0.73	0.73	0.73		0.088	0.011	0.066	0.066	0.066	0.066	-
Titanium-pigment	50	0.001	0.001	0.001	6.2	0.001	0.001		0.002	0.003	0.002	0.002	0.003	0.002	-
Gas-fired power plant (400 MW e)	600 [b]				230				-	-	-	-	-	-	-
Oil extraction	3 500				540					217	174	174	174	174	
Gas extraction	72 000 [b]				500					2.7	32	32	32	32	

a Zirconium.
b 10^6 m^3 a^{-1}.

Table 29
Maximum effective doses from natural radionuclides released from typical installations or operations of the mineral processing industry
[L18]

Industry	*Maximum effective dose rate (μSv a^{-1})*		
	External irradiation	*Air dispersion pathways*	*Water dispersion pathways*
Elementary phosphorus production	130	2	<0.4
Phosphoric acid production	8	~2 000 [b]	2
Fertilizer production	20	<0.4	15
Primary iron and steel production	8	<0.4	3
Coal tar processing	4	<0.4	
Cokes production	4	<0.4	
Coal-fired power plant	12	<0.4	4
Gas-fired power plant	<0.4	<0.4	–
Oil and gas extraction	2 [a]	<0.4 [b]	
Cement production	5	<0.4	
Ceramic industry plant	<0.4	<0.4	
Mineral sands handling	60	<0.4	320
Titanium pigment production	<0.4	<0.4	1

a Inhalation dose (radon) due to land fill with harbour sludge below a residential area.
b Rather uncertain value.

Table 30
Distribution of population with respect to total exposure to natural sources

Region / country	*Population (10^3) with various levels of total exposure*										
	< 1.5 mSv a^{-1}	*1.5-1.99 mSv a^{-1}*	*2.0-2.99 mSv a^{-1}*	*3.0-3.99 mSv a^{-1}*	*4.0-4.99 mSv a^{-1}*	*5.0-5.99 mSv a^{-1}*	*6.0-6.99 mSv a^{-1}*	*7.0-7.99 mSv a^{-1}*	*8.0-8.99 mSv a^{-1}*	*9.0-9.99 mSv a^{-1}*	*>10 mSv a^{-1}*
East Asia											
China (Hong Kong SAR)		1 130	4 370	770	160	46	11	5	5		
Japan	60 211	63 306	1 247								
Malaysia	12 490	4 240									
North Europe											
Denmark		800	2 800	900	400	200	50	30	30	20	20
Finland	223	1 376	2 039	687	310	154	87	82	37	29	123
Lithuania	1 680	854	770	275	80	14	28	19	5	5	
West Europe											
Belgium	280	3 300	4 500	1400	440	150	70	30	14	7	29
Netherlands	14 023	779	701	39	39						
East Europe											
Bulgaria		990	6 051	1 836							
Hungary	560	2 101	3 325	1 683	1 010	633	388	184	102	61	153
Romania		4 653	8 717	5 312	2 951	567	500				
Russian Federation	80 941	32 000	20 027	6 642	3 067	1 685	1 029	675	465	333	1 236
South Europe											
Albania	50	200	2 500	300	300	100	50				
Italy	150	15 125	25 800	7 825	4 175	2 175	1 025	500	150	150	200
Portugal	3 650	2 076	1 994	792	770	113	39				
Total	174 258	131 800	80 471	27 691	13 542	5 791	3 266	1 520	803	605	1 761
Fraction of total	0.39	0.30	0.18	0.063	0.031	0.013	0.007	0.003	0.002	0.001	0.004
Cumulative total	174 258	306 058	386 529	414 220	427 762	433 553	436 819	438 339	439 142	439 747	441 508
Cumulative fraction	0.39	0.69	0.88	0.94	0.97	0.982	0.989	0.993	0.995	0.996	1.0

Table 31
Average worldwide exposure to natural radiation sources

Source of exposure	*Annual effective dose (mSv)*	
	Average	*Typical range*
Cosmic radiation		
Directly ionizing and photon component	0.28 (0.30) [a]	
Neutron component	0.10 (0.08)	
Cosmogenic radionuclides	0.01 (0.01)	
Total cosmic and cosmogenic	0.39	0.3–1.0 [b]
External terrestrial radiation		
Outdoors	0.07 (0.07)	
Indoors	0.41 (0.39)	
Total external terrestrial radiation	0.48	0.3–0.6 [c]
Inhalation exposure		
Uranium and thorium series	0.006 (0.01)	
Radon (^{222}Rn)	1.15 (1.2)	
Thoron (^{220}Rn)	0.10 (0.07)	
Total inhalation exposure	1.26	0.2–10 [d]
Ingestion exposure		
^{40}K	0.17 (0.17)	
Uranium and thorium series	0.12 (0.06)	
Total ingestion exposure	0.29	0.2–0.8 [e]
Total	2.4	1–10

a Result of previous assessment [U3] in parentheses.
b Range from sea level to high ground elevation.
c Depending on radionuclide composition of soil and building materials.
d Depending on indoor accumulation of radon gas.
e Depending on radionuclide composition of foods and drinking water.

References

PART A

Responses to UNSCEAR Survey of Exposures from natural radiation sources

Country	*Respondent*
Albania	R. Kushe. Institute of Nuclear Physics, Tirana S. Bushati. Department of Radiometry, Center of Geophysical and Geochemical Exploration, Tirana
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18 May 2016

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Volume I

Annex C (Exposures to the public from man-made sources of radiation)

Corrigendum

1. **Page 255, table 33, section entitled "PWRs", Republic of Korea**

   For the entry for Kori 1-4 in the column for 1992, *for* 16 *read* 1.8

   For the entry for Ulchin 1-2 in the column for 1991, *for* 0.086 *read* 0.0086

2. **Page 258, table 33, section entitled "HWRs", Republic of Korea**

   For the entry for Wolsong 1-2 in the column for 1995, *for* 0.052 *read* 0.0052

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ANNEX C

Exposures to the public from man-made sources of radiation

CONTENTS

INTRODUCTION

1. The Committee has continually kept under review the exposures of the world population resulting from releases to the environment of radioactive materials from man-made sources. Exposures from such sources reviewed in the UNSCEAR 1993 Report [U3] included atmospheric nuclear testing, underground nuclear testing, nuclear weapons fabrication, nuclear power production, radioisotope production and uses, and accidents at various locations. New information on man-made environmental exposures is considered in this Annex.

2. The testing of nuclear weapons in the atmosphere was the most significant cause of exposure of the world population to man-made environmental sources of radiation. The practice continued from 1945 to 1980. Although the testing has ceased and the Committee's assessment of global doses based on measured ^{90}Sr deposition remains an accurate evaluation of the resulting exposures, particularly for long-lived radionuclides, new data on the yields of individual tests have been made available. These allow more detailed calculations of the dispersal of radionuclides throughout the world following the injection of debris into the atmosphere. Estimates of total deposition and doses from individual radionuclides are re-evaluated in this Annex, which also considers exposures to individuals who lived near the test sites. Previous estimates of exposures from atmospheric testing were based on accumulated average doses (dose commitments), but there is interest as well in the annual doses received by individuals. Annual dose estimates are derived in this Annex.

3. Following the cessation of atmospheric testing, nuclear weapons continued to be tested underground. Several further underground tests were conducted in 1998. Underground testing results only infrequently in releases of radionuclides to the environment and the exposure of individuals. Beyond the testing of nuclear weapons, the military fuel cycle, involving the production of weapons materials and the fabrication of the weapons, has also resulted in releases of radioactive materials to the environment. Information on exposures in areas surrounding the industrial sites of nuclear materials production and weapons fabrication are considered in this Annex. Both historical and contemporary data not previously reviewed by the Committee are presented.

4. Nuclear power production continues in a number of countries, where it is an important component of electrical energy generation. Rather complete monitoring and reporting of radionuclides released, especially from nuclear reactors, provide adequate data to allow analysing exposures from this source. Data on annual releases for 1990–1997 and analysis of longer-term trends are included in this Annex. Another continuing practice, radioisotope production and uses, involves at the production stage rather trivial doses that can be only roughly estimated from the total size of the industry worldwide and some approximate figures on fractional releases of the radionuclides produced. The Committee previously assessed these exposures. The exposures of family members of patients who received therapeutic treatments with ^{131}I are considered in this Annex.

5. Another source of exposures that may be considered to be man-made is the use of fuels or materials containing naturally occurring radionuclides. These are referred to as enhanced natural radiation exposures. It has been the practice of the Committee to evaluate these along with other exposures from natural radiation. These evaluations are included in Annex B, "*Exposures from natural radiation sources*".

I. TESTING AND PRODUCTION OF NUCLEAR WEAPONS

6. The testing of nuclear weapons in the atmosphere, which took place from 1945 until 1980, involved unrestrained releases of radioactive materials directly to the environment and caused the largest collective dose thus far from man-made sources of radiation. Previous assessments by the Committee of the total collective dose to the world population in the UNSCEAR 1982 and 1993 Reports [U3, U6] are complete and still valid. In the latter Report [U3], transfer coefficients are given for the dose per unit release or per unit deposition density for over 20 radionuclides for the inhalation, ingestion, and external exposure pathways.

7. The evaluation of doses to the hemispheric and world populations from this practice has been based on the

measured global deposition density of ^{90}Sr, limited measurements of ^{95}Zr deposition, and on estimated ratios of the deposition of other radionuclides to these. The annual depositions of ^{90}Sr were measured in some detail during the years when testing in the atmosphere took place. This has meant that the collective doses could be evaluated more directly and with less uncertainty than would be the case if uncertain estimates of the amounts of radionuclides produced in the tests and their dispersion in the environment had to be relied on. However, lack of sufficient data for other, and especially the shorter-lived, radionuclides limits the reliability of the estimated ratios to ^{95}Zr and ^{90}Sr.

8. In recent years some further details of atmospheric nuclear testing have become available. In particular, the numbers and total yields of the explosions have been officially reported, providing reliable basic input data, and estimates are being made of the local doses to populations living in the vicinities of the test sites. This information is taken note of by the Committee to complete the historical record of this practice.

9. In its previous assessments, the Committee emphasized the estimation of the collective doses from atmospheric nuclear testing and did not evaluate annual doses in detail. Approximate magnitudes of annual doses were presented in the UNSCEAR 1982 Report [U6]. The unfolding of collective doses to derive annual doses is presented below in more detail to illustrate the time dependence of contributions to the annual effective doses already received by the world population from various radionuclides and to estimate the future annual effective doses from residual contamination.

10. The production of nuclear weapons involves securing quantities of enriched uranium or plutonium for fission devices and of tritium and deuterium for fusion devices. The fuel cycle for military purposes is similar to that for nuclear electrical energy generation: uranium mining and milling, enrichment, fuel fabrication, reactor operation, and reprocessing. Releases of radionuclides may occur at all the various stages but particularly during reprocessing and plutonium separation. Initial information on exposures from the operation of military fuel cycle installations was included in the UNSCEAR 1993 Report [U3]. Some further data are summarized in this Chapter. Discharges and hence exposures were greatest in the early years when nuclear arsenals were being established.

A. ATMOSPHERIC TESTS

1. Number and yields of tests

11. Further information on the number and yields of atmospheric nuclear tests has been reported by the countries that conducted the tests. In the UNSCEAR 1993 Report [U3], the number of tests by all countries was adjusted from 423 to 520, an increase of more than 20%. The total has since been modified slightly, and at the same time the estimated total and fission yields have been revised downwards.

12. Compilations of data on atmospheric nuclear tests have been published within the last few years, first by the United States [D4], then by the former Soviet Union [M2], the United Kingdom [J3], and France [D3]. Information was provided on the date of each test, its name or designation, location, type, purpose, and the total explosive yield. To verify production amounts of important globally dispersed fission radionuclides, it would also be necessary to know the fission yield of each test or series of tests.

13. The data on atmospheric nuclear tests needed by the Committee for exposure evaluations are given in Table 1, and a summary for each country and each test site is provided in Table 2. The date, type, and total explosive yield of individual tests are as reported by the country. In a few cases, the total yields reported by the United States and the former Soviet Union were indefinite (“low”, “sub megatonne”, or within a designated range). Specific values for summations and analyses were estimated based on assumptions given in the footnotes to Table 1.

14. Assumptions are also needed to estimate the fission and fusion yields of individual tests. Relatively low yield explosions may be assumed to be due to fission only, and very high yield explosions were thermonuclear tests with substantial fusion yields. For the purpose of obtaining values for Table 1, all tests smaller than 0.1 Mt total yield were assumed to be due only to fission, unless otherwise indicated. For tests in the range 0.5–5 Mt, fission yields averaging about 50% have been reported to be representative [G4], and that value has been assumed here. For tests in the range 0.1–0.5 Mt, a fission yield of 67% is assumed. There were 17 tests in the range 5–25 Mt. With no other indications available, fission yields of 33% were assumed in Table 1 for these tests. However, the fission yields of tests by the United States were arbitrarily adjusted to agree with the reported total fission yields for the years 1952, 1954, and 1958. The large variation in assumed fission yields for the high-yield tests conducted in these years is consistent with unofficial reports that the test of 31 October 1952 (Mike) had a relatively high fission yield and with the confirmation that some high-yield tests had very high fission ratios [D7]. The largest test, 50 Mt, conducted by the former Soviet Union in 1961, was reported to have a fission yield of 3% and a fusion yield of 97% [M2]. Special design measures were taken to obtain such a high fusion yield.

15. It would be desirable to have further information on the fission and fusion yields of atmospheric nuclear tests to substantiate the somewhat arbitrary assumptions that must be made, particularly for the tests of the former Soviet Union. Because the largest atmospheric nuclear tests ($\geq$4 Mt) made such substantial contribution to the fission, fusion, and total yields, they are listed separately in Table 3. These 25 tests account for nearly 66% of the total explosive yield of all tests and about 55% of the estimated fission yields. Tests with yields greater than 1 Mt accounted for over 90% of the total fission yield.

16. Some exceptions to the general fission/fusion assumptions can be made for the atmospheric tests conducted by China. These tests occurred in the latter part of the test period, and the individual tests were relatively well separated in time. It was thus possible to obtain independent estimates of fission yields from the stratospheric monitoring of radionuclides that took place regularly throughout this testing period [K7, K8, K9, K10, L7, L8, T5]. The estimates of fission yields from ^{90}Sr and ^{95}Zr stratospheric inventories include some inconsistencies and uncertainties, but the direct evidence is used in preference to the assumptions.

17. The annual number and yields of atmospheric tests by all countries are summarized in Table 4 and illustrated in Figure I. The number of tests (Figure I, upper diagram) was greatest during 1951–1958 and 1961–1962. There was a moratorium in 1959, which was largely observed in 1960, as well. The most active years of testing from the standpoint of the total explosive yields (Figure I, lower diagram) were 1962, 1961, 1958, and 1954. The total number of atmospheric tests by all countries was 543, and the total yield was 440 Mt. The fission yield of all atmospheric tests is estimated at present to be 189 Mt.

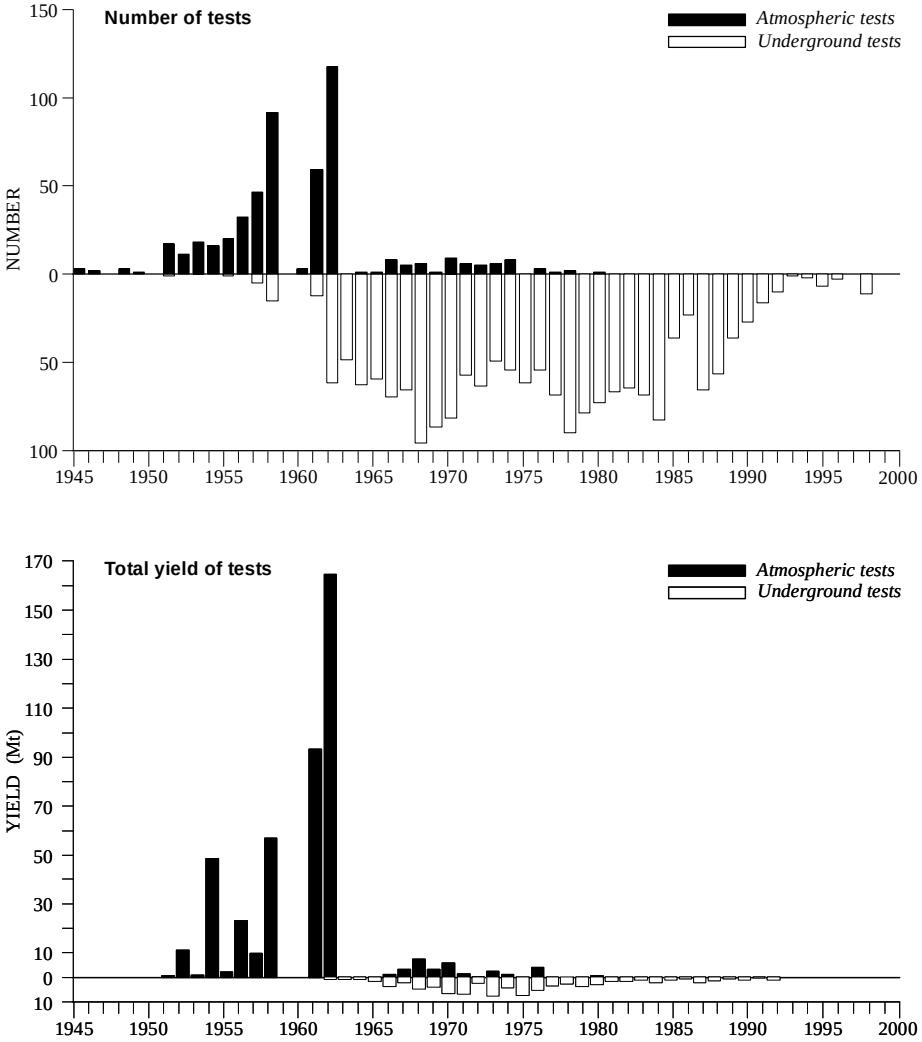


Figure I. Tests of nuclear weapons in the atmosphere and underground.

2. Dispersion and deposition of radioactive debris

18. Nuclear weapons tests were conducted at various locations on and above the earth's surface, including mountings on towers, placement on barges on the ocean surface, suspensions from balloons, drops from airplanes, and high-altitude launchings by rockets. Depending on the location of the explosion (altitude and latitude) the radioactive debris entered the local, regional, or global environment. For tests conducted on the earth's surface, a portion of the radioactive debris is deposited at the site of the test (local fallout) and regionally up to several thousand km downwind (intermediate fallout). This fraction varies from test to test depending on the meteorological conditions, height of the test, the type of surface and surrounding material (water, soil, tower, balloon, etc.). For refractory radionuclides such as ^{95}Zr and ^{144}Ce, 50% of the debris is assumed to be deposited locally in the immediate vicinity of the test site and a further 25% is deposited regionally [B9, B10, H5]. For volatile radionuclides such as ^{90}Sr, ^{137}Cs and ^{131}I, 50% of the fission yield, on average, is assumed deposited locally and regionally [P1]. The remainder of the debris and all of the debris from airbursts is widely dispersed in the atmosphere. Airbursts are defined as tests occurring at or above a height in metres of $55\ Y^{0.4}$, where Y is the total yield in kilotonnes [P1].

19. Depending on the conditions of a test, the radioactive debris can be initially partitioned or apportioned into various regions of the atmosphere. A basic compartment diagram representing atmospheric regions and the predominant atmospheric transport processes is shown in Figure II. This representation was developed to describe atmospheric dispersion and deposition of radioactive debris produced in atmospheric nuclear testing [B1, U6]. The atmosphere is divided into equatorial and polar regions (from 0° to 30° and 30° to 90° latitude, respectively). The troposphere height is variable with latitude and season, but for modelling purposes it is assumed to be at an average altitude of 9 km in the polar region and 17 km in the equatorial region. The lower stratosphere is assumed to extend to 17 km and 24 km, respectively, in the two regions and the upper stratosphere to 50 km in both regions. Only a few tests injected material above the upper stratosphere, designated the high atmosphere, which extends to several hundred kilometres and includes the remainder of the region from which debris will eventually be deposited on the earth's surface.

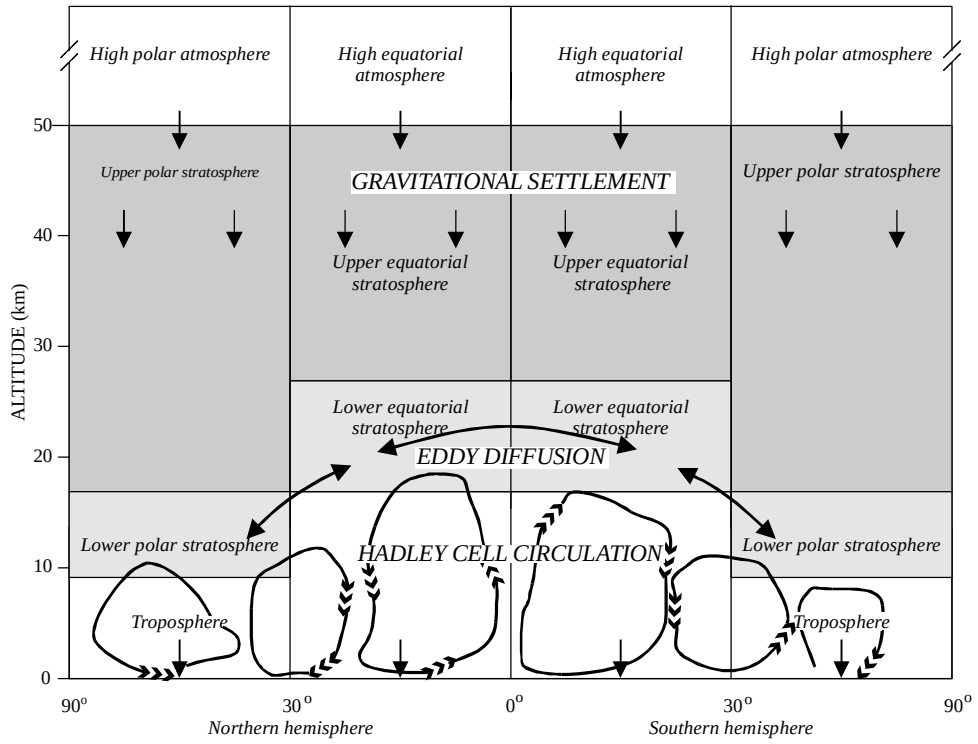


Figure II. Atmospheric regions and the predominant atmospheric transport processes.

20. Apportionment of debris in the atmosphere is based on the stabilization heights of cloud formation following the explosion. Empirical values derived from a number of observations are given in Table 5 [P1]. These results were used for the earlier estimates of fallout production from atmospheric testing that were quoted in the UNSCEAR 1982 Report [U6]. Adjustments can now be made according to the revised values of total yields and the fission yield estimates given in Table 1. The partitioned yield estimates are included in Tables 1 and 2, and annual injections into the various atmospheric regions are summarized in Table 6. The estimate of the relative fractions of debris injected into the stratosphere and troposphere for a particular test with yield less than several megatonnes is somewhat uncertain for several reasons. The empirical estimates were only available for equatorial tests and were highly variable [F5]. Values for polar latitudes are based on meteorological considerations [F5], and the height of the troposphere varies seasonally.

21. Partitioning of debris into atmospheric regions was initially formulated for the equatorial and polar regions. Injections from the Chinese test site at Lop Nor (40°N) indicate that a temperate region formulation would also be useful. This was not apparent for earlier tests at the Nevada test site (37°N) or the Semipalatinsk test site (52°N) because there was relatively little or no stratospheric input from tests at these sites. Releases from temperate sites can be partitioned by averaging the equatorial and polar results. Basically, this averaging procedure reduces the input to the upper stratospheric region compared with the partitioning for a polar release. Details of the assumptions, justified by the empirical nature of the modelling, are specified in the footnote to Table 6.

22. With the indication of the type of test given in Table 1, the apportionment of fission yield corresponding to local and more widespread tropospheric and stratospheric portions has been made in Tables 1, 2 and 4. The tropospheric and stratospheric injections listed in these Tables are for volatile radionuclides (e.g. ^{90}Sr, ^{137}Cs) and do not reflect the additional local and regional deposition that occurred for refractory radionuclides (e.g. ^{95}Zr, ^{144}Ce).

23. As indicated in the summary Tables 2 and 4, the locally and regionally deposited debris amounts to about 29 Mt (for volatile elements). Therefore, about 160 Mt is estimated to

have been widely dispersed, contributing to global fallout. This latter value, inferred from yield information, may be compared with the value of 155 Mt derived from global ^{90}Sr measurements (604 PBq deposited worldwide divided by the production estimate of 3.9 PBq Mt^{-1}). Since about 2%–3% of ^{90}Sr decayed before deposition, the total dispersed amount (injection into atmosphere) inferred from measurements is also about 160 Mt. The fission yield estimates thus provide much better agreement with the measured deposition (corresponding to 155 Mt) than the previous fission yield estimates of 189 Mt [B1, U6]. The estimate of the total debris deposited locally and regionally is somewhat uncertain due to the likely high variations from test to test, however, as seen, this component is a small fraction of the debris injected into the global atmosphere, and thus this uncertainty will have only a small impact on the uncertainty in the total global ^{90}Sr deposition.

24. From extensive monitoring following individual tests and for the entire period of dispersion and deposition, considerable information was gained on the movement and mixing processes in the atmosphere. The radioactive debris served as a tracer material. Aerosols in the atmosphere descend by gravity at the highest altitudes and are transported with the general air movements at lower levels. Eddy diffusion causes irregular migration of air masses in the general directions indicated in Figure II in the lower stratosphere and upper troposphere. The circular air flow pattern in the troposphere at lower latitudes is termed Hadley cell circulation. These cells increase or decrease in size and shift latitudinally with season. The balanced pattern shown in Figure II is that for the months of March, April, May, and September, October, November. The mean residence time of aerosols in the lower stratosphere ranges from 3 to 12 months in the polar regions and 8 to 24 months in the equatorial regions. The specific seasonal values, determined from empirical fitting to fallout radionuclide measurements, are indicated in Figure III. The most rapid removal occurs during the spring months. Removal half-times to the next lower region from the upper atmosphere are 6 to 9 months and from the high atmosphere, 24 months was found to be representative [B1]. A removal half-time of infinity (∞) in Figure III means that no transfer takes place via the particular pathway during that season of the year.

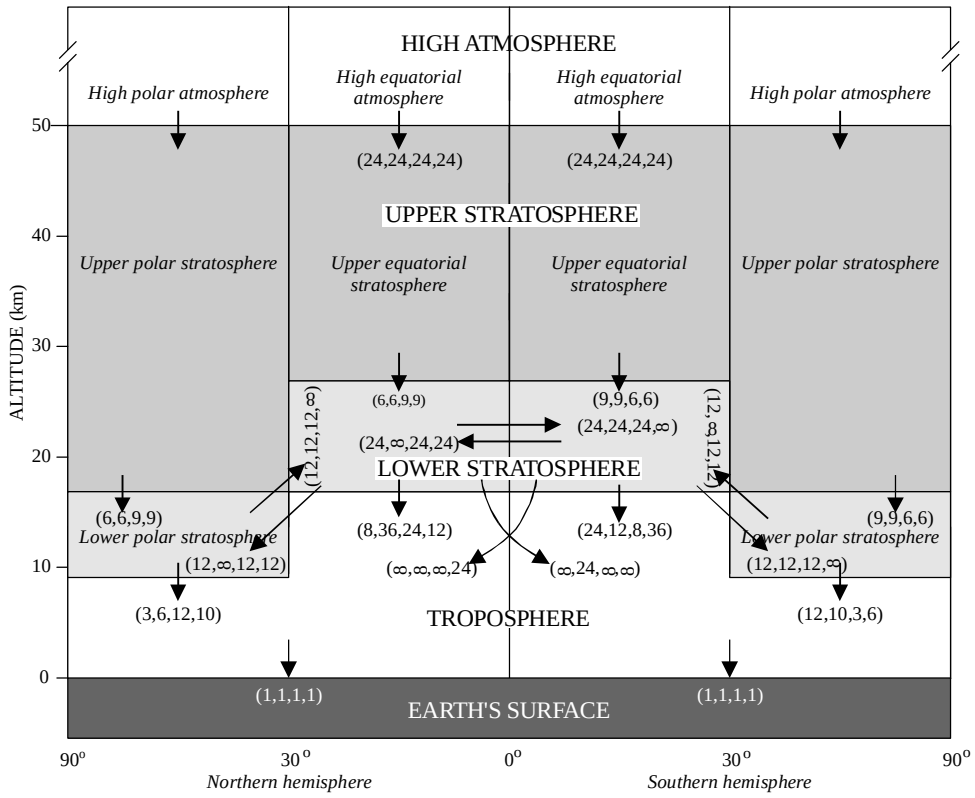


Figure III. Schematic diagram of transfers between atmospheric regions and the earth's surface considered in the empirical atmospheric model [B1].

The numbers in parentheses are the removal half-times (in months) for the yearly quarters in the following order: March-April-May, June-July-August, September-October-November, December-January-February.

25. An empirical atmospheric compartmental model based on Figures II and III had been used to estimate surface air concentrations and deposition of long-lived fallout radionuclides starting with estimated fission production yields of each test [B1]. However, since rather complete measurements of ^{90}Sr in air and deposition were available and there were uncertainties in the reported fission yields, this modelling work was not pursued. Improved estimates of fission yields changes this situation and allows the possibility of examining in greater detail the deposition of other radionuclides, such as ^{106}Ru and ^{144}Ce, and of projecting the measurement records beyond levels

of detection capabilities. Estimates can also be made for short-lived radionuclides such as ^{95}Zr, however the uncertainty will be greater, since most of the deposition from these radionuclides is from highly uncertain fractions of the total debris that were injected into the troposphere or deposited locally and regionally.

26. The parameters of the empirical model were set by comparisons with data on tracer radionuclides released in some of the tests at specific times, such as ^{185}W, ^{109}Cd, and ^{54}Mn, as well as with the longer-term records of ^{90}Sr. The fit of the calculation to the ^{90}Sr data in surface air is shown in Figure IV for the northern hemisphere (upper diagram) and for the southern hemisphere (lower diagram). With the available estimates of fission yields of individual atmospheric tests, the model matches rather well the monthly data that show seasonal variations in the concentrations. The model indicates the total ^{90}Sr inventory in the hemispheric troposphere. This has been converted to a concentration with use of a volume parameter of 0.0001 Bq m^{-3} per PBq, empirically determined from the ^{90}Sr data for mid-latitudes [B1]. Annual average calculated and measured concentrations of ^{90}Sr in surface air of the mid-latitude regions are summarized in Table 7.

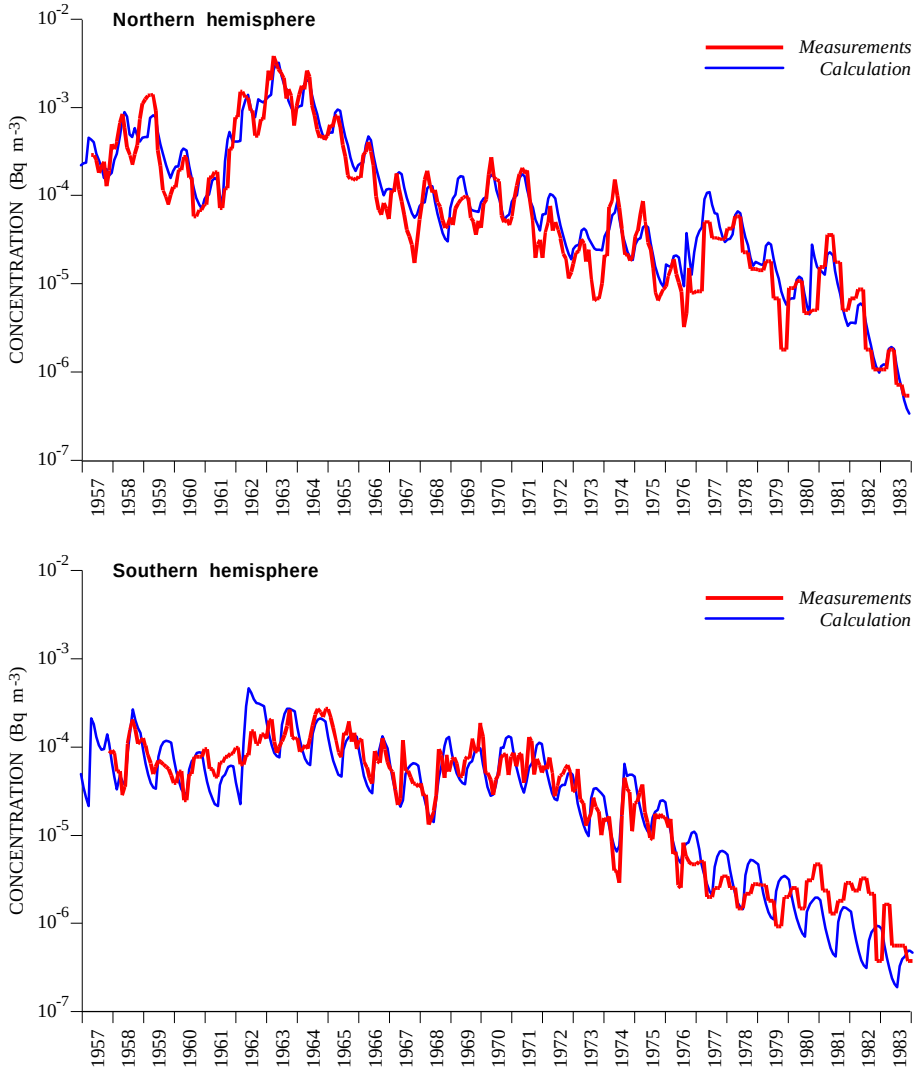


Figure IV. Strontium-90 concentration in air in the mid-latitude regions.
The measurements averaged over several sites are compared with results of the atmospheric model calculation.

27. Measurements of ^{90}Sr in surface air were made routinely at a number of locations around the world. A global surface–air monitoring network was maintained by the United States Naval Research Laboratory from 1957 to 1962 [L6] and continued by the Environmental Measurements Laboratory of the United States Department of Energy from 1963 to 1983 [F4]. After 1983, the levels were undetectable with the methods used. The representative measured concentrations of ^{90}Sr in air shown in Figure IV are derived from averaging the results of several sites in the mid-latitudes of both hemispheres (see footnotes to Table 7).

28. Some slight deviations between the measured and calculated results of ^{90}Sr in air may be due to inaccurate estimation of injection amounts or of the initial partitioning of debris in the atmosphere or to variations in the measured results or in the meteorology that may occur

from year to year. Furthermore, the measured results at the chosen representative mid-latitude sites may not be representative of the entire hemisphere as calculated from the model, particularly for years with relatively large tropospheric injections from low-latitude test sites. Debris injected into the equatorial troposphere at low latitudes will likely remain in a low latitude band due to the Hadley circulation patterns, as illustrated in Figure II. Some deviations for tests conducted at high-latitude sites have also occurred, for example the rapid depletion of the polar stratosphere in 1959 following the 1958 Soviet tests was indicated by the measurements. Also notable is the absence of a peak in 1962 in the southern hemisphere following injections into the troposphere and stratosphere of the equatorial region from tests in that year. Further deviations occur beyond 1980, when the low levels reached by the measured concentrations become uncertain and some enhancement from resuspension of ground deposits may become relatively more important.

29. Long-term monitoring of ^{90}Sr deposition based on precipitation sampling was conducted with global networks operated by the Environmental Measurements Laboratory of the United States [H1] and the Harwell Laboratory of the United Kingdom [P3]. Quite comparable results were obtained. An earlier monitoring network based on gummed-film detectors at more than a hundred stations in many countries was operated from 1952 to 1959 by the Health and Safety Laboratory, which became the Environmental Measurements Laboratory, in the United States [H8]. The results of deposition densities at individual sites have been averaged within latitude bands and multiplied by the area of the bands to obtain estimates of the hemispheric and global deposition amounts. The annual results are shown in Figure V for the northern hemisphere (upper diagram) and southern hemisphere (lower diagram) and are compared to the estimates derived from the atmospheric model. The agreement is quite close until the early 1980s, when uncertainties in the measurements began to increase.

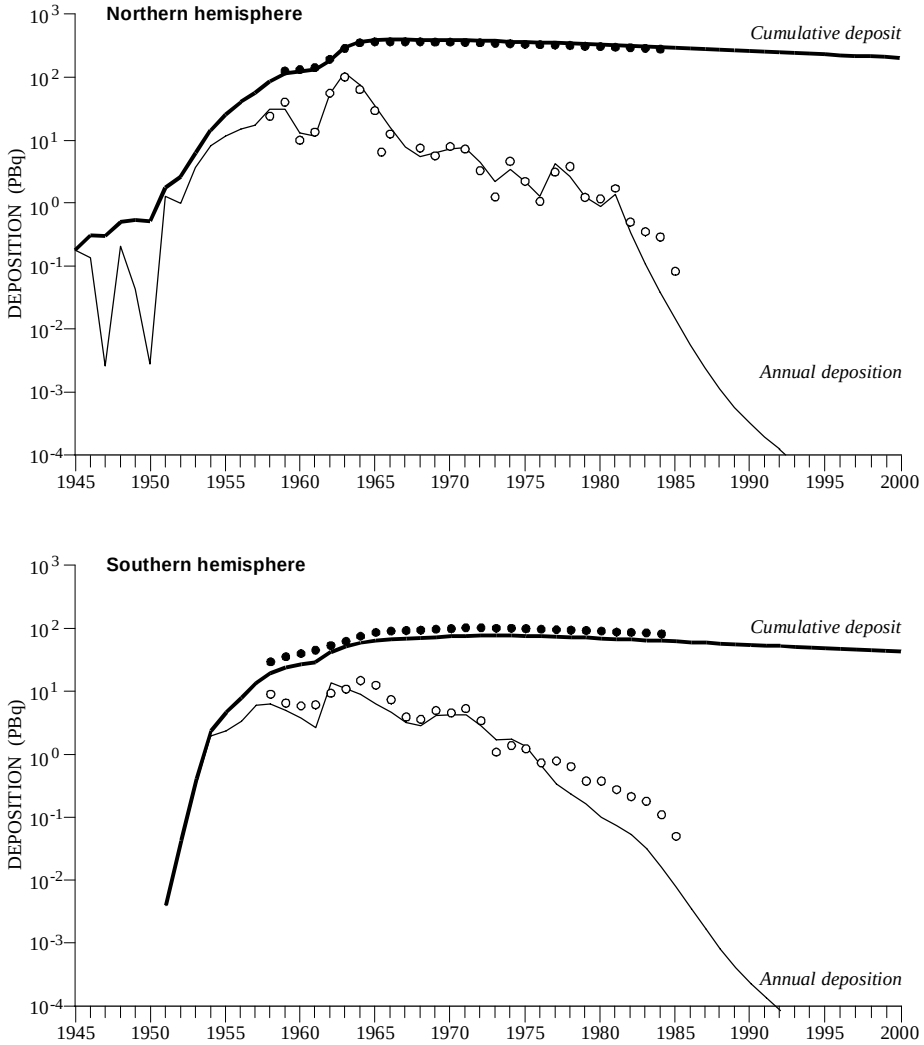


Figure V. Hemispheric depositions of ^{90}Sr determined from global network measurements (points) and from atmospheric model calculations (lines).

30. Using the atmospheric model and the estimated fission yields of individual tests, it is possible to distinguish the contributions of the test programmes of individual countries to the annual deposition of ^{90}Sr. This is illustrated in Figure VI. In the northern hemisphere the contributions from the test programme of the United States dominated before

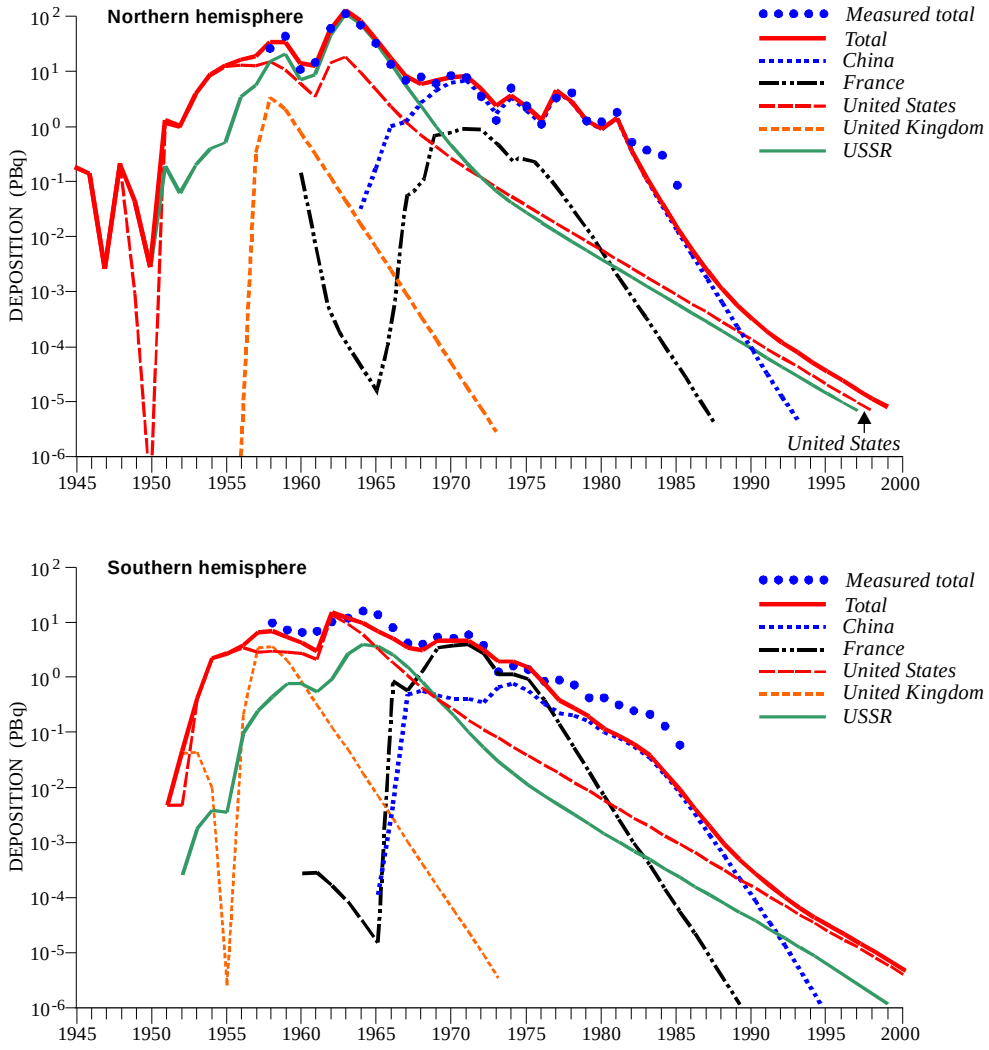


Figure VI. Components of strontium-90 deposition from test programmes of countries calculated from fission yields of tests with the atmospheric model.

1958. From 1959 until 1967 the test programme of the former Soviet Union contributed the greatest amounts to annual ^{90}Sr deposition, and from 1968 until 1988 the deposition was primarily from the Chinese tests. In the southern hemisphere, the annual deposition was greatest from the tests of the United States before 1964 except for 1957 and 1958, when the equatorial tests of the United Kingdom took place. Subsequently, the greatest contributors to annual deposition were the former Soviet Union during 1965–1967, France during 1968–1976, and China during 1977–1988. Owing to slower removal of debris from inventories in the high atmosphere and upper stratosphere, the deposition of the test programmes of the United States and the former Soviet Union predominate again in the 1990s, although at levels too low to be measurable.

31. A summary of the annual hemispheric totals of measured and calculated ^{90}Sr deposition is given in Table 7. The deposition rate of ^{90}Sr was generally greater by a factor of about 5 in the northern hemisphere from 1953 to 1965 and from 1977 to 1983. From 1967 to 1977 and since 1985, the fallout rates in both hemispheres have been roughly the same. The model results indicate a total global deposition of 610 PBq. Using the measurement results preferentially, when available, the global deposition amount of ^{90}Sr is unchanged, although the measurements indicate a slightly smaller proportion of the total deposition in the northern hemisphere than indicated by the calculations. The previous estimate of the total deposition based on measurement results and measured cumulative deposition up to 1958 was 604 PBq. The calculated results indicate a decay of about 2%–3% of the injected amount of ^{90}Sr prior to deposition (injected amount 160.5 Mt × 3.9 PBq Mt^{-1} = 626 PBq; deposited amount 610 PBq or 97.4% of the injected amount), corresponding to an average residence time of debris in the atmosphere of about 1.1 years. The measured result of 604 PBq suggests an average residence time of about 1.3 years. The global cumulative deposit reached a maximum in 1967–1972 of 460 PBq (Table 7). By the year 2000, this will have decayed to 250 PBq.

32. Since most of the atmospheric tests were conducted in the northern hemisphere, the deposition amounts are greater there than in the southern hemisphere. Because of the preferential exchange of air between the stratosphere and troposphere in the mid-latitudes of the hemisphere and the air

circulation patterns in the troposphere, there is enhanced deposition in the temperate regions and decreased deposition (by a factor of about 2) in the equatorial and polar regions. The latitudinal distribution of ^{90}Sr deposition determined from the global measurements is given in Table 8. This latitudinal variation is only valid for long-lived radionuclides, for which most of the deposition was from debris originally injected into the stratosphere. As the half-life of the radionuclide decreases, a larger fraction of the fallout was from injections into the troposphere, since larger fractions of the stratospheric amounts decay during the relatively long stratospheric residence times. The variation with latitude for these radionuclides thus will depend more on the latitude of injection. (The model indicates that about 90% of the deposited ^{90}Sr is from stratospheric debris, while for ^{95}Zr only about one third is due to stratospheric debris and for ^{131}I, less than 5%).

33. With demonstrated good agreement for ^{90}Sr obtainable with the empirical atmospheric model, the concentrations in air and the deposition of other long-lived radionuclides can be calculated. Previously, estimates were made from ratios to ^{90}Sr values. The atmospheric model can take better account of decay prior to deposition and can start with the fission production values that are independent of estimates for other radionuclides. The model can be very usefully applied for short-lived radionuclides that could not be adequately monitored at the time the testing occurred. However, because the deposition of these short-lived radionuclides is so dependent on the fractions injected into the troposphere and the amounts of local and intermediate fallout, the model deposition estimates are less reliable, and the results need to be adjusted to agree with available data.

34. The radionuclides produced and globally dispersed in atmospheric nuclear testing that are important from a dosimetric point of view are listed in Table 9. These are the radionuclides that were also considered in the UNSCEAR 1993 Report (Annex B, Table 1) [U3]. For fission radionuclides, the production per unit energy released in the tests assumes 1.45 10^{26} fissions Mt^{-1}. Multiplying by the fission yield and the decay constant gives the normalized activity production. For radionuclides produced in fusion reactions or by activation primarily in thermonuclear tests (^{3}H, ^{14}C, ^{54}Mn, ^{55}Fe), the normalized production can be estimated from measured inventories in the environment and the associated total fusion energy of all tests. The values for ^{54}Mn and ^{55}Fe are those quoted in the UNSCEAR 1993 Report [U3], which may yet be adjusted to take into account better estimates of the inventories and the total fusion energy of tests. The production of transuranic radionuclides has been inferred from ratios to ^{90}Sr, as measured in deposition. These values are thus unchanged from previous estimates [U3]. The total production of radionuclides in atmospheric testing associated with the globally dispersed debris (excluding local deposition at the test sites and regional deposition) and based on revised estimates of fission and fusion energies is given in the last column of Table 9. The fission yields in Table 9, which are assumed to be representative of all atmospheric tests, are those for thermonuclear tests, since these contributed over 90% of the debris. The fission yields for ^{89}Sr and ^{125}Sb has been revised slightly from those previously used [U3], based on the production ratios for thermonuclear tests reported by Hicks [H6].

35. The input data to the atmospheric model for the calculation of worldwide deposition of radionuclides produced in atmospheric testing are the fission and fusion yields of individual tests (Table 1), the normalized production of radionuclides (Table 9), and the atmospheric partitioning assumptions (Tables 5 and 6). Because atmospheric transport is seasonal, it is necessary to work with monthly values of input and to calculate monthly deposition. For short-lived radionuclides it is necessary to use daily values to adequately account for decay before deposition. The total annual deposition results are presented in Table 10 for each hemisphere and for the world. Because thermonuclear fission yields were used, the estimates for years with mostly low-yield tests are somewhat less certain, since the fission yields for low-yield tests for some radionuclides vary significantly depending on the mixture of fissile material used.

36. Only for ^{90}Sr are there adequate measurements of hemispheric deposition that could be used in place of the calculated results. Limited data are available for ^{89}Sr from the sampling network of the United States [H7]. Some data on other radionuclides are also available for a few sites during particular time periods. There are only minor discrepancies in calculated and measured results for ^{90}Sr, but the measured results are used preferentially in Table 10, i.e. 1958–1985. An important component of the residual global contamination from atmospheric testing is ^{137}Cs. Because of the similarity in the half-life of ^{137}Cs (30.07 a) and ^{90}Sr (28.78 a), deposition occurs according to the ratio of fission yields and (inversely) half-lives: ^{137}Cs/^{90}Sr = 1.5. Thus, the estimates of ^{137}Cs in Table 10 are based on this ratio times the measured ^{90}Sr deposition for the period 1958–1985. The estimates for ^{144}Ce, ^{106}Ru and ^{125}Sb, ^{54}Mn and ^{55}Fe are based solely on the calculated results. The calculated results for the refractory radionuclides, ^{95}Zr, ^{141}Ce, ^{144}Ce, ^{54}Mn, and ^{55}Fe take into account the higher local and intermediate deposition discussed earlier. The estimates of annual deposition of ^{95}Zr, ^{91}Y, ^{89}Sr, ^{103}Ru, ^{141}Ce, ^{140}Ba, and ^{131}I have been normalized to the total depositions reported at the bottom of Table 10. The estimates of total deposition are based on comparisons with available data, production ratios, and relative half-lives. The ratios of total deposition for these radionuclides to ^{90}Sr differ somewhat from those reported in the UNSCEAR 1993 Report [U3], because of revised assessment of the available data as well as an adjustment to account for a greater proportion of deposition at low latitudes than assumed earlier.

37. A basic indication of deposition amounts determined by measurements and needed in dose calculations is the deposition density, the activity of deposited radionuclides per unit ground surface area. Global measurements of ^{90}Sr are related to the areas of the 10° latitude bands in which the measurements were made. These areas are given in Table 8. From the evaluated fractional deposition in each band, the total hemispheric deposition is apportioned and the deposition densities determined. By weighting these results with the populations in the bands, the population-weighted deposition

density for the hemisphere is obtained. With 89% of the world population in the northern hemisphere and 11% in the southern hemisphere, the hemispheric results may be weighted accordingly to obtain the world average deposition density. This latitudinal apportionment is valid only for the long-lived radionuclides for which most of the deposition originated from debris injected into the stratosphere. For short-lived radionuclides, for which most of the deposition was from debris injected into the troposphere, adjustments must be made to account for the increased deposition at low latitudes resulting from tests of the United States and the United Kingdom in the Pacific. Since the population in the northern hemisphere is about equally divided between latitudes greater and less than 30°, an increase in the relative fraction of the deposition below 30° has only a small impact (about 10%) on the population-weighted deposition density. However, because 86% of the population of the southern hemisphere lives between 0°–30° latitude and almost all of the debris injected into the southern hemisphere troposphere was at latitudes less than 30°, the value to convert from total deposition to population-weighted deposition density for short-lived radionuclides (half-lives less than 30 days) for months in which the input was primarily from United States tests in the Pacific would be 6.7 rather than 3.74 (see Table 8). An intermediate weight of 5.7 based on 75% of the debris from tropospheric injections and 25% from stratospheric injections would be more appropriate for radionuclides with half-lives of about 30 to 100 days.

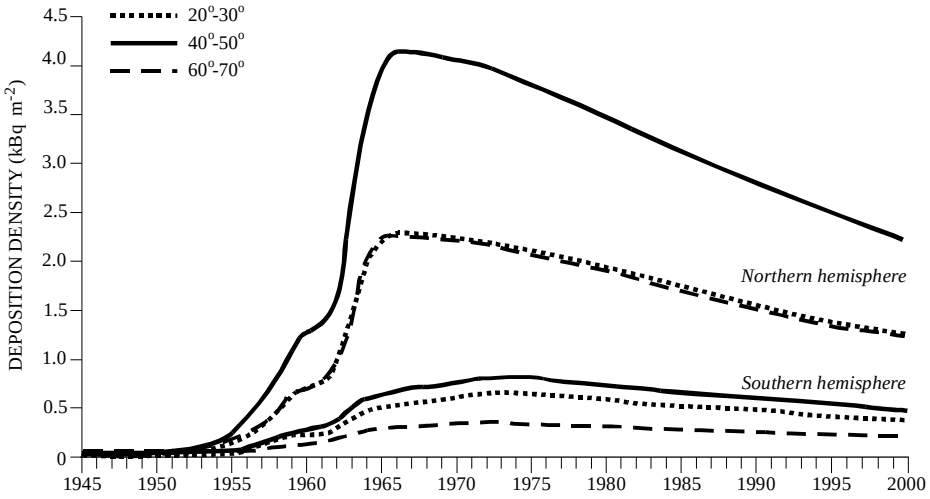


Figure VII. Caesium-137 deposition density in the northern and southern hemispheres calculated from fission production amounts with the atmospheric model.

38. The hemispheric and world average cumulative deposition densities are given in Table 11. The monthly deposition results from the atmospheric model have been averaged over the year. The model accounts for decay during the month of deposition as well as after deposition. The total deposition for long-lived radionuclides (half-life >100 d) in the hemisphere is multiplied by the parameters in Table 8 (4.65 and 3.74 Bq m^{-2} per PBq in the northern and southern hemisphere, respectively) to obtain the population-weighted deposition densities of Table 11. For radionuclides with half-lives between 30 and 100 d, and <30 d, factors of 5.7 and 6.7 Bq m^{-2} per PBq, respectively, were used for the southern hemisphere. A value of 4.0 was used for the northern hemisphere for all short-lived radionuclides. The world average is the population-weighted sum of the hemispheric values: 0.89 times the average population-weighted deposition density of the northern hemisphere plus 0.11 times the average population-weighted deposition density of the southern hemisphere. For the long-lived radionuclides, the deposition densities in particular latitudinal regions may be obtained with use of the factor given in the last column of Table 8. For example, the deposition density for ^{90}Sr in the 40°–50° latitude region of the northern hemisphere is 1.5 times the northern hemisphere average value.

39. An important component of the residual radiation background caused by deposition of radionuclides produced in atmospheric testing is that of ^{137}Cs. Calculated deposition densities of ^{137}Cs in various latitude regions are shown in Figure VII. These levels were perturbed by additional deposition from the Chernobyl accident in 1986, especially in European countries.

40. The world average deposition densities of radionuclides produced in atmospheric testing are illustrated in Figure VIII. Considerable variations are noted for the short-lived radionuclides, and these have by now decayed to negligible levels. When the tests were taking place, the deposition densities of several short-lived radionuclides, especially ^{144}Ce, ^{106}Ru, and ^{95}Zr, were highest, but since 1965, ^{137}Cs and ^{90}Sr dominate in the residual cumulative deposit.

41. The summations of the annual deposition densities of Table 11 give the integrated deposition densities (Bq a m^{-2}) for the radionuclides. Only for ^{90}Sr and ^{137}Cs are there significant contributions beyond the year 2000. The total in Table 11 extended for all time (1945 to infinity) may also be obtained from the total deposited amounts (Table 10) multiplied by the mean lives of the radionuclides ($1/\lambda$ = half-life ÷ ln2) and the appropriate population-weighted conversion factor from Table 8. This demonstrates the consistency of the annual calculation of deposition and the cumulative deposition density.

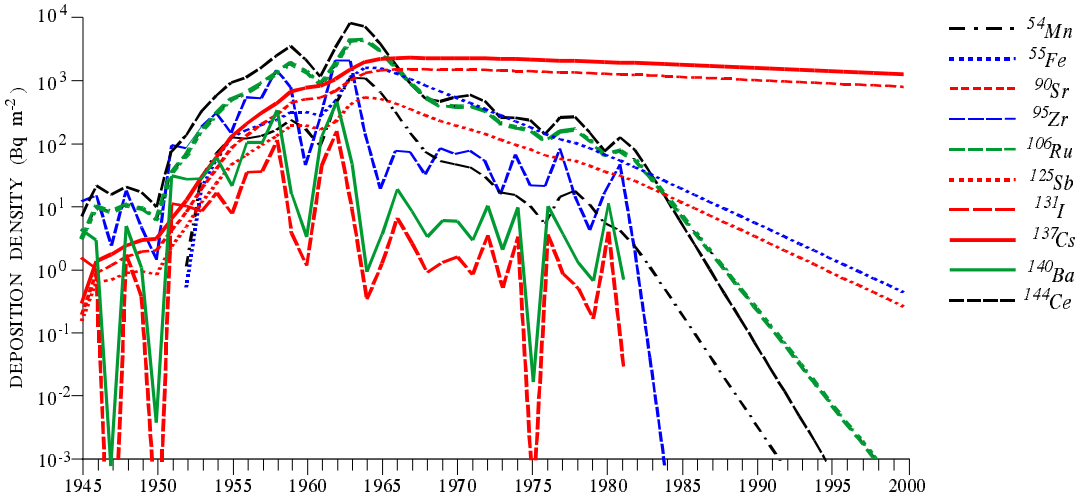


Figure VIII. Worldwide population-weighted cumulative deposition density of radionuclides produced in atmospheric testing. *The monthly calculated results have been averaged over each year. Several short-lived radionuclides with half-lives and deposition patterns intermediate between ^{140}Ba and ^{95}Zr are not shown.*

3. Annual doses from global fallout

42. The Committee provided a rough indication of the average annual doses to the world population from fallout radionuclides in the UNSCEAR 1982 Report [U6]. For 1958–1979, the maximum dose rate was estimated to be 0.14 mSv a^{-1} in 1963, and it had decreased by almost an order of magnitude by 1979. Using available empirical models, the annual doses can be estimated in much more detail. The results of this exercise are presented in this Section.

43. The basic input to dose calculations from fallout radionuclides has been the measured deposition density of ^{90}Sr. The measured annual hemispheric deposition amounts for representative mid-latitude sites are listed in Table 7. The measurements, which began in 1958, were continued until 1985. By then the stratospheric inventory from atmospheric tests was largely depleted. Some of the monitoring sites were affected by the Chernobyl accident in 1986. Subsequently, a low, constant level of deposition has been measured that reflects resuspended soil particles [A4, I5]. Longer-lived radionuclides in global fallout other than ^{90}Sr have also been monitored, but they have been present in relatively constant ratios to ^{90}Sr. For short-lived radionuclides (half-life <100 days), decay before deposition is significant. For these radionuclides, the pattern of deposition was previously taken to be that of ^{95}Zr, with the magnitude estimated from the average value of the ratio determined by available measurements. The empirical atmospheric model with input from individual nuclear tests now allows the time course of deposition of all radionuclides produced in atmospheric testing to be determined in greater detail and with better general accuracy.

44. The general procedures for deriving dose estimates from the measured or calculated deposition densities of radionuclides are presented in Annex A, "*Dose assessment methodologies*". It is only necessary to summarize here the values of transfer coefficients needed for the annual dose evaluations for the various pathways: external, inhalation, and ingestion. The transfer coefficients P_{25} used to evaluate the effective dose committed by unit deposition density of a radionuclide were given in the UNSCEAR 1993 Report (Annex B, Table 8) [U3].

45. Of the radionuclides contributing to external exposure, only ^{137}Cs has a half-life greater than a few years. For this radionuclide the depth distribution in soil has been taken to correspond to a relaxation length of 3 cm. Previous assessments of external doses from fallout assumed a plane source distribution for the other radionuclides [U3, U4]. This assumption is now altered to provide a more realistic basis for the dose estimation. A relaxation length of 3 cm is also used for the other long-lived radionuclides (half-lives >100 days). For radionuclides with half-lives between 30 and 100 days, a relaxation length of 1 cm is more appropriate. For the other short-lived radionuclides (half-lives <30 days), a relaxation length of 0.1 cm is assumed rather than a plane source, to account for ground roughness. The chosen relaxation lengths are consistent with the values used in the UNSCEAR 1988 Report [U5] to estimate external exposures from the Chernobyl accident and more adequately reflect the observed penetration of the radionuclides into the soil with time. The parameters required to calculate the annual effective doses from external irradiation are summarized in Table 12.

46. For the external irradiation pathway, the effective dose rate per unit deposition density is derived by multiplying the dose rate in air per unit deposition density by the conversion factor 0.7, which relates the dose rate in air to the effective dose, and the occupancy-shielding factor, 0.2 fractional time outdoors + 0.8 fractional time indoors × 0.2 building shielding = 0.36. The average annual effective dose is then obtained by multiplying by the average annual deposition density.

47. The values of annual doses due to external exposure from radionuclides produced in atmospheric testing are given in Table 13. The components of the world average

external dose are illustrated in Figure IX (upper diagram). The short-lived radionuclide ^{95}Zr, with its decay product ^{95}Nb, was the main contributor to external exposure during active testing. Of less significance were ^{106}Ru, ^{54}Mn, and ^{144}Ce. Beginning in 1966, ^{137}Cs became the most important contributor, and presently it is the only radionuclide contributing to continuing external exposure from deposited radionuclides.

48. Several radionuclides contribute to exposure via the ingestion pathway. They are listed, along with the transfer coefficients, in Table 12. For the short-lived radionuclides (^{131}I, ^{140}Ba, ^{89}Sr), the exposures occur within weeks or months following deposition. For annual dose rates, it is sufficient to assume that the exposures occur evenly over the mean life of the radionuclide. The transfer coefficients relating dose rate to deposition density are obtained by dividing the transfer coefficients for the committed dose [U3] by the radioactive mean lives. These are the entries in Table 12.

49. In previous UNSCEAR assessments, exposures via the ingestion pathway from the longer-lived radionuclides ^{90}Sr and ^{137}Cs have been derived from empirical transfer models applied to the measured deposition density of ^{90}Sr (the ^{137}Cs to ^{90}Sr ratio of 1.5 is used to derive the deposition density of ^{137}Cs). The parameters of the models were evaluated from regression fits to the measured concentrations of these radionuclides in diet and the human body. These models apply to continuing deposition throughout the year, as occurred during fallout deposition. Thus, the seasonal variability in transfers to diet is averaged out in a single annual value.

50. The model used to describe the transfer of ^{90}Sr or ^{137}Cs from deposition to diet is of the form

$$C_{d,i} = b_1 F_i + b_2 F_{i-1} + b_3 \sum_{n=1}^{\infty} e^{-\lambda' n} F_{i-n} \qquad (1)$$

where $C_{d,i}$ is the concentration of the radionuclide in a food component d or in the total diet in the year i due to the deposition density rate F_i in the year i, F_{i-1} in the previous year, and the sum of the deposition density rates in all previous years, reduced by exponential decay. The exponential decay with decay constant λ' reflects both radioactive decay and environmental loss of the radionuclide. The coefficients b_i and the parameter λ' are determined by regression analysis of measured deposition and diet data. The coefficients b_i represent the transfer per unit annual deposition in the first year (b_1), primarily from direct deposition, in the second year (b_2), from lagged use of stored food and uptake from the surface deposit, and in subsequent years (b_3), from transfer via root uptake from the accumulated deposit.

51. The transfer from diet to the human body (bone) for ^{90}Sr is described by a two-component model:

$$C_{b,i} = c\, C_{d,i} + g \sum_{m=0}^{\infty} e^{-\lambda_b m} C_{d,i-m} \qquad (2)$$

where $C_{b,i}$ is the concentration of ^{90}Sr in bone in the year i, c is a coefficient for short-term retention, and g is a coefficient for longer-term retention, with removal governed by the decay constant λ_b. The parameters c, g, and λ_b are determined by regression fits to monitoring data.

52. The retention of ^{137}Cs in the body is relatively short-term (retention half-time of around 100 days). The annual dose per unit intake can therefore be expressed by a single transfer coefficient, P_{34}, which applies to the year of intake. The annual doses from ^{90}Sr and ^{137}Cs in the body are evaluated using the transfer coefficient P_{45}. The values of the transfer coefficients used in calculating the annual effective dose from ingestion of ^{90}Sr and ^{137}Cs, derived from long-term monitoring, are given in Annex A, "*Dose assessment methodologies*".

53. Further exposure via ingestion of longer-lived radionuclides occurs from ^{55}Fe and the transuranium elements. The doses committed from the transuranium radionuclides are very small, and the contributions to annual doses are negligible. A transfer model does not exist for ^{55}Fe. Its half-life is only 2.73 years; therefore, it is assumed, as for the short-lived radionuclides, that the dose-rate transfer coefficient is equal to the commitment transfer coefficient [U3] divided by the radioactive mean life. This result is entered in Table 12.

54. The components of annual dose via the ingestion pathway from radionuclides produced in atmospheric testing are listed in Table 14 and illustrated in Figure IX (middle diagram). During active testing, ^{137}Cs was the most significant component, owing to its more immediate transfer to diet and delivery of dose. Because of the longer-term, continuing transfer of ^{90}Sr to diet and its longer retention in the body, this radionuclide became the most important contributor to dose beginning in 1967. The short-lived radionuclides have been relatively insignificant contributors to ingestion exposure (see Figure IX).

55. For the inhalation pathway, exposures depend on the concentrations of radionuclides in air, but because of the association between concentrations in air and deposition densities through the deposition velocity, the transfer coefficients for the dose from inhalation can be given in terms of the measured deposition densities of the radionuclides. These transfer coefficients, P_{25}, were given in the UNSCEAR 1993 Report (Annex B, Table 8) [U3] and are repeated here in Table 12. These are the committed doses per unit intake. The dose from inhalation can be assumed delivered in the same year that the deposition occurred. Subsequent exposures from resuspension are accounted for in the measured air concentrations and the derived deposition velocity, and although these exposures may continue for a few more years, including all of the exposure in the year of initial deposition does not introduce much error.

56. The estimates of annual doses from the inhalation of radionuclides produced in atmospheric testing are given in Table 15, and several of the components are illustrated in Figure IX (lower diagram). Important contributors to

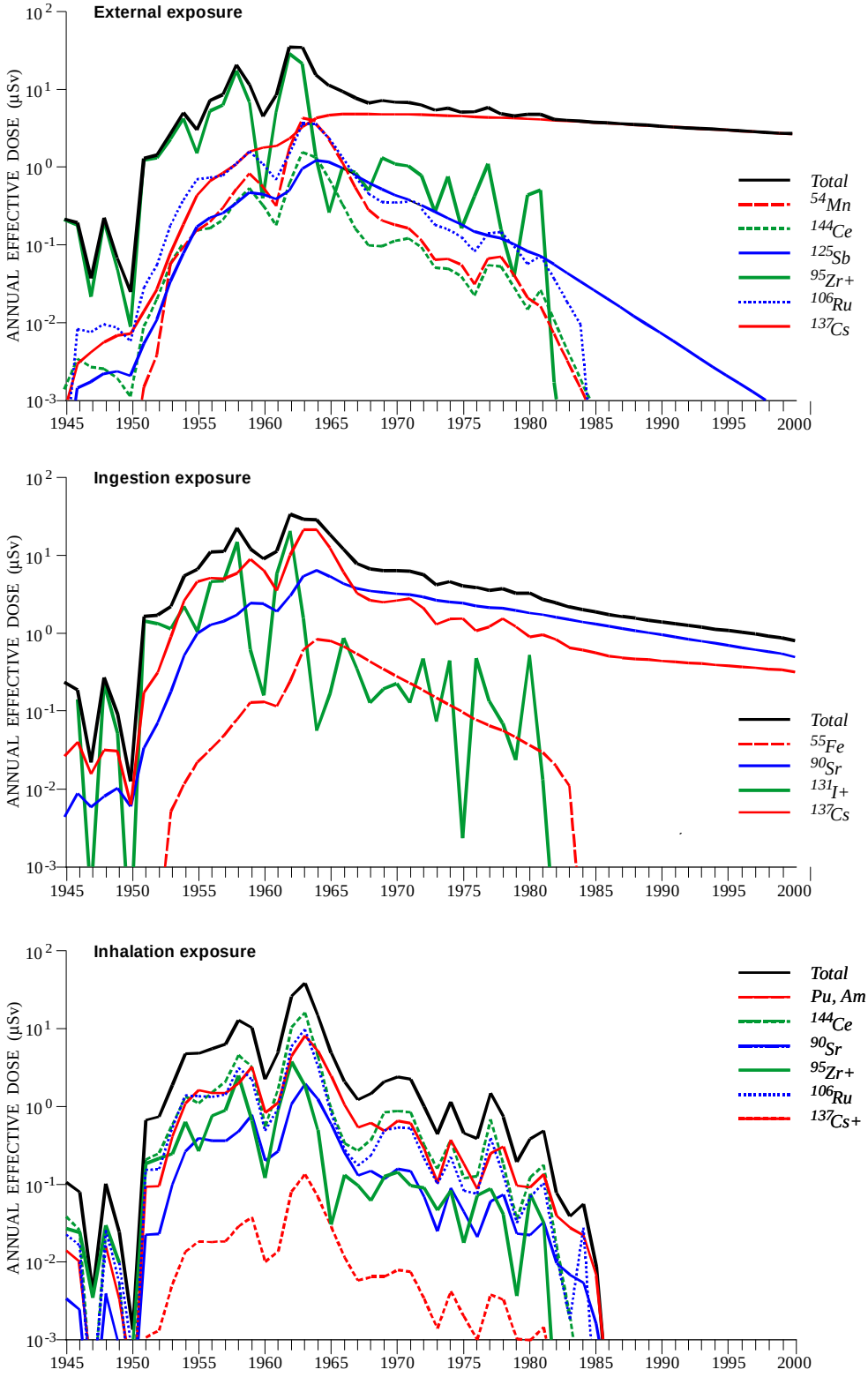


Figure IX. Worldwide average doses from radionuclides produced in atmospheric testing.
External exposure: *Contributions from radionuclides ^{131}I, ^{140}Ba, ^{144}Ce, ^{106}Ru are included with ^{95}Zr;*
Ingestion exposure: *Contributions from ^{90}Sr and ^{140}Ba are included with ^{131}I;*
Inhalation exposure: *Contributions from short-lived radionuclides (^{131}I, ^{140}Ba, ^{141}Ce, ^{103}Ru, ^{89}Sr, ^{91}Y) are included with ^{95}Zr and from intermediate-lived radionuclides (^{54}Mn, ^{125}Sb, ^{55}Fe) are included with ^{137}Cs.*

inhalation exposure were ^{144}Ce, the transuranic radionuclides, ^{106}Ru, ^{91}Y, ^{95}Zr, and ^{89}Sr. Deposition, and thus the concentrations of these radionuclides in air, dropped rapidly once atmospheric testing ceased in 1980. Even for the long-lived transuranic radionuclides, inhalation exposure became insignificant after 1985.

57. One further contribution to annual exposures comes from the globally dispersed radionuclides ^{3}H and ^{14}C. In both cases, there is no external exposure and only negligible exposure from inhalation. Exposure arises most entirely from the ingestion pathway. Global models have been formulated to describe the dispersion and long-term behaviours of these radionuclides in the environment. Estimates of the annual doses from ^{3}H and ^{14}C produced in atmospheric testing are included in Table 14 and illustrated in Figure X.

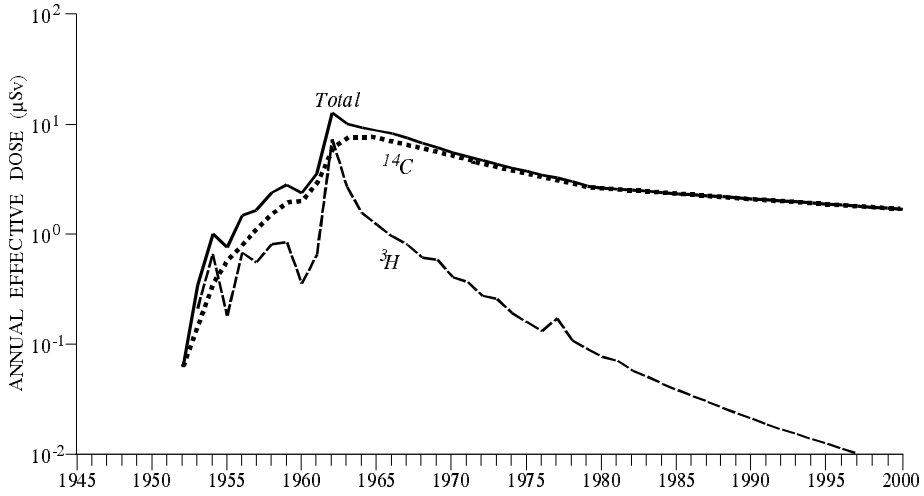


Figure X. Worldwide average dose (mainly from ingestion pathway) from globally dispersed ^{3}H and ^{14}C.

58. The annual doses from tritium have been evaluated using the seven-compartment model presented by the United States National Council on Radiation Protection and Measurements (NCRP) [N1]. With volumes and transfer rates applicable for the hydrological cycle of the world and intake of water by humans assumed to be 33% from the atmosphere, 53% from surface fresh waters, 13.3% from groundwater, and 0.7% from ocean surface water (through fish) [N1], the dose per unit release is 0.06 nGy PBq^{-1}. Further details of the model are presented in Annex A, "*Dose assessment methodologies*".

59. The annual doses from ^{14}C have been derived using the multi-compartment model described in Annex A, "*Dose assessment methodologies*". The estimates are only approximate, since widespread, immediate mixing in large regions is assumed in the model formulation. To compensate for this, the hemispheric values have been adjusted to an initial ratio of 4 to 1 in the northern and southern hemispheres, reflecting the deposition pattern of longer-lived radionuclides. This ratio was maintained through 1970 and then reduced uniformly to a ratio of 1 to 1 by the year 2000, representing assumed completion of uniform mixing throughout the world. This procedure provides more realistic estimates of doses in the hemispheres, but does not affect the estimated global average. The average annual global effective dose from ^{14}C produced in atmospheric nuclear testing was at a maximum, 7.7 μSv, in 1964 and has decreased by a factor of 4 since that time. The dose would be estimated to be somewhat less when account is taken of the input of stable carbon into the atmosphere from fossil fuel burning, which dilutes the ^{14}C.

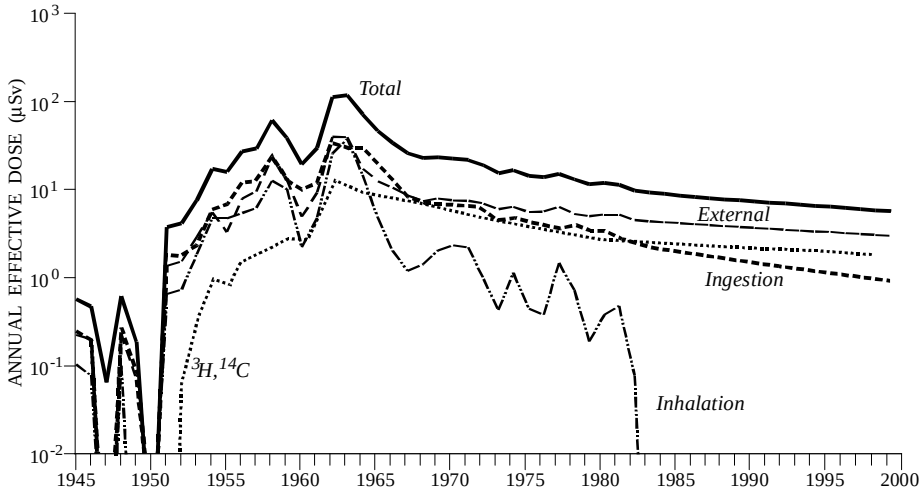


Figure XI. Contributions of pathways to worldwide average dose from radionuclides produced in atmospheric testing.

60. The estimates of the total annual effective doses from radionuclides produced in atmospheric nuclear testing are summarized in Table 16, and the world average contributions from the main pathways are illustrated in Figure XI. These results are for the hemispheric- and world-population-weighted averages of deposition of fallout radionuclides. The doses in more specific regions of the world may be obtained by adjusting to the latitudinal distribution of deposition determined from measurement of ^{90}Sr (Table 8). In the temperate zones ($40^\circ - 50^\circ$), the annual doses from long-lived radionuclides are higher than the hemispheric averages by factors of 1.5 in the northern hemisphere and 1.65 in the southern hemisphere. For the short-lived radionuclides (see paragraph 37), the distribution with latitude is more uniform in the northern hemisphere, while the doses in the temperate zones of the southern hemisphere are about one third less than the hemispheric average. The hemispheric average annual dose was highest in 1963 in the northern hemisphere (0.13 mSv) and in 1962 in the southern hemisphere (0.06 mSv).

61. The estimated world average annual dose from atmospheric nuclear testing was highest in 1963 (0.11 mSv) and subsequently declined to less than 0.006 mSv in the 1990s. External exposure generally made the highest contributions to annual doses, when the annual doses from ^{14}C and ^{3}H are not included, initially by short-lived radionuclides and subsequently by ^{137}Cs. Both external and ingestion exposure peaked in 1962. The annual doses at present are due almost equally to external irradiation (53%) and ingestion exposures (47%). The dose from ^{14}C (30% of the total) now exceeds that from ingestion of other radionuclides. The doses yet to be delivered at future times are also indicated in Table 16. The summation of annual doses for all time defines the dose commitment, which is the dose quantity previously evaluated in UNSCEAR assessments of the exposure from atmospheric nuclear testing [U3]. With use of the model calculations, the revised external dose coefficients, and the re-evaluation of the total deposition of short-lived radionuclides, the present dose estimates for some radionuclides differ slightly from the previous assessment, although the current estimated total effective dose commitment to the world population, 3.5 mSv, is little different from the result given in the UNSCEAR 1993 Report [U3], 3.7 mSv.

4. Local and regional exposures

62. Since atmospheric nuclear tests were conducted in relatively remote areas, exposures of local populations did not contribute significantly to the world collective dose from this practice. Nevertheless, those individuals living downwind of the test sites received greater-than-average doses. In addition, individuals who might now or in the future occupy contaminated areas of the former test sites could receive exposures through external or internal pathways. Efforts are being made to evaluate these sites to guide possible rehabilitation and resettlement, and work is continuing to reconstruct the exposure conditions and to estimate the local and regional doses that were received at the time of the tests. Available information was presented in the UNSCEAR 1993 Report [U3] and is summarized here in Table 17. Further results, although still not systematic and complete, are presented in this Section. It will be necessary to add details as the dose reconstruction efforts progress.

63. The locations of several test sites are shown in Figures XII, XIII, and XIV. The areas within a few hundred kilometres of the site are generally designated as local and those within a few thousand kilometres, regional. Distances of 500 km and 1,000 km from the test sites are delineated in the figures for reference purposes. The exposed populations were generally only those living in downwind, generally eastward directions.

(a) Nevada test site

64. The Nevada test site in the United States was the location for 86 atmospheric nuclear tests: 83 tests were conducted from 1951 to 1958, and 3 more tests were conducted in 1962. Additional cratering tests also injected debris into the atmosphere [N10]. Local areas were affected by relatively few tests, but for those few tests they were much more affected than more distant areas of the United States, which received less deposition and exposure but were more evenly affected by a larger number of tests. The external exposures to local populations were estimated at the time of testing to be low; however, public concern about the health impact of the exposures grew. As a consequence, rather detailed dose reconstruction projects were undertaken in the 1980s.

65. Estimates of external exposures from atmospheric tests at the Nevada test site were reported by Anspaugh et al. [A1, A3]. Results were derived from survey meter and film badge measurements for 300 communities in the local areas (<300 km) around the test site in Nevada and in southwestern Utah. The distribution of individual cumulative exposures is given in Table 18. The effective dose exceeded 3 mSv in 20% of the population of 180,000. The highest effective doses were in the range 60–90 mSv, and the population-weighted average value was 2.8 mSv [A1]. The exposures resulted primarily from short-lived gamma-emitters (half-lives <100 days). The estimates were based on outdoor occupancy of 50% and a building shielding factor of 0.5; the usual UNSCEAR assumptions are 20% and 0.2, respectively. Most of the exposures resulted from relatively few events; 90% of the cumulative collective dose of 470 man Sv resulted from 17 events, the most significant being test Harry on 19 May 1953 (180 man Sv), test Bee on 22 March 1955 (70 man Sv), and test Smoky on 31 August 1957 (50 man Sv) [A3]. Collective doses that included areas further downwind, encompassing all of Nevada and Utah and parts of several other western states, were estimated to have been even greater than for the local area, about 10,000 man Sv, primarily due to the exposure of the large population areas around Salt Lake City [A7, B9]. All of the United States received some fallout from Nevada weapons tests [B10]. Beck and Krey [B11] reported cumulative doses from external exposure averaged about 1 mSv to persons living in the midwest and east of the country.

66. Internal exposures resulting from atmospheric testing at the Nevada test site have been estimated from deposition measurements and an environmental transfer model [K2, W2]. Absorbed doses to organs and tissues from internal exposure were substantially less than those from external exposure, with the exception of the thyroid, in which ^{131}I from ingestion of milk contributed relatively higher doses. Estimates of absorbed doses in the thyroid of 3,545 locally exposed individuals ranged from 0 to 4.6 Gy; the average was 98 mGy and the median 25 mGy [T4]. Five individuals received absorbed doses greater than 3 Gy, and all of them drank milk from a family-owned goat [T4]. The collective absorbed dose to the thyroid of the population of states in the western United States was estimated to be 140,000 man Gy [A7]. An extensive study has been completed by the National Cancer Institute of the United States of thyroid doses in all counties of the United States from ^{131}I deposition following the atmospheric tests in Nevada [B6, N10]. The individual thyroid doses ranged up to 100 mGy in local areas. For the entire population of the United States, the estimate was 20 mGy, with a collective absorbed dose of 4 10^6 man Gy. Although not involving exposure, it should be noted that plutonium migration from an underground nuclear test conducted at the Nevada Test Site was detected 30 years following the test in a ground water monitoring well 1.3 km from the test location [K12]. In this very arid region, no migration had been anticipated. The authors concluded that colloid-facilitated transport was implicated in the field findings.

(b) Bikini, Enewetak test sites

67. An extensive nuclear test programme was conducted by the United States at locations in the Pacific (Table 1). The test resulting in the most significant local exposures was the thermonuclear test Bravo on 28 February 1954 at Bikini Atoll. Unexpectedly heavy fallout occurred in the local area eastward of the atoll (Figure XII). Within a few hours of the explosion, fallout particles descended on Rongelap and Ailinginae atolls, 200 km from Bikini, exposing 82 persons. The Japanese fishing vessel Lucky Dragon was also in this area, and 23 fishermen were exposed. Farther east, exposures occurred at Rongerik Atoll (28 United States servicemen) and Utrik Atoll (159 persons). These individuals were evacuated within a few days of the initial exposures.

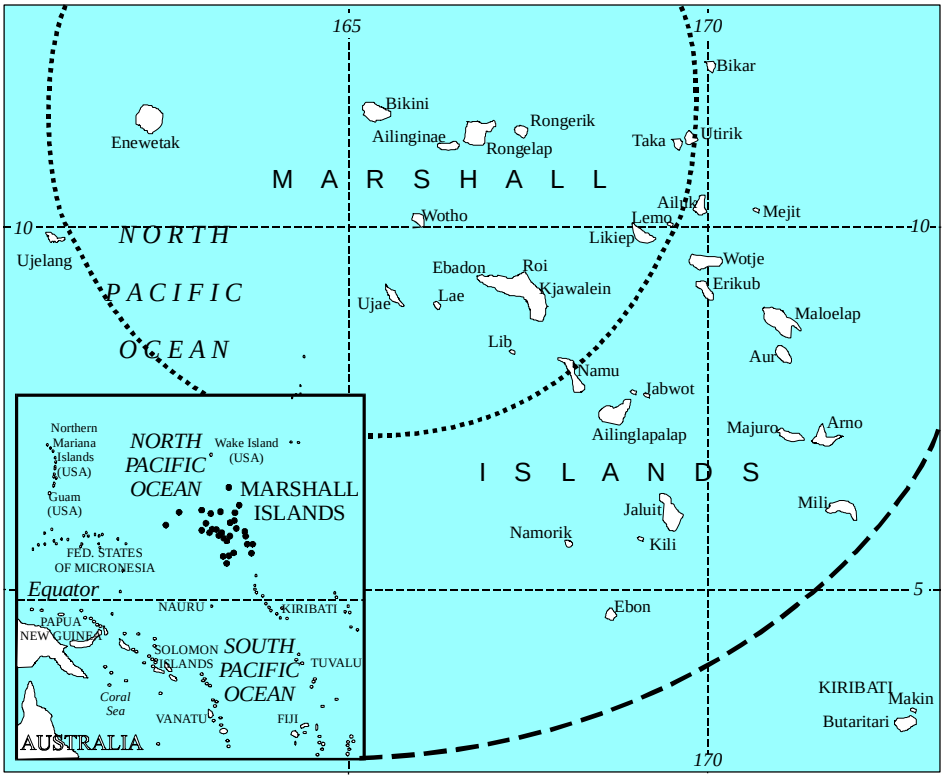


Figure XII. Bikini and Enewetak test sites.

The inner dotted circle indicates a distance of 500 km, the outer dashed circle 1,000 km from the test sites.

68. Average external exposures from the Bravo test, mainly from short-lived radionuclides, ranged from 1.9 Sv on Rongelap (67 persons, including 3 *in utero*), 1.1 Sv on Ailinginae (19 persons, including 1 *in utero*), and 0.1 Sv on Utrik (167 persons, including 8 *in utero*) [L4]. The collective dose from the exposures received by these individuals before evacuation was, therefore, 160 man Sv. Thyroid doses from several isotopes of iodine and tellurium and from external gamma radiation were estimated to be 12 Gy on average (42 Gy maximum) to adults, 22 Gy (82 Gy maximum) to children of 9 years, and 52 Gy (200 Gy maximum) to infants of 1 year [L4].

69. The external exposure from the Bravo test to the servicemen on Rongerik Atoll was 0.8 Sv [L4]. For the 23 Japanese fishermen, the external exposures from the fallout

deposition on deck ranged from 1.7 to 6 Sv, mostly received on the first day of the fallout but continuing for 14 days, until the ship arrived in its port [C9]. The thyroid doses to the fishermen were estimated to have been 0.2–1.2 Gy from ^{131}I, based on external counting, but since other short-lived iodine isotopes were also present, the total doses to the thyroid from inhalation during a period of five hours were estimated to have been 0.8–4.5 Gy [C9].

70. There seem to have been no other tests that caused significant exposures to the population in the Pacific region. The populations of the atolls where tests were conducted had been relocated prior to the testing. Exposures to residual radiation levels on Utrik and Rongelap atolls to residents who returned to these islands in 1954 and 1957, respectively, were of the order of 20–30 mSv over the following 20-year period from external irradiation and 20–140 mSv from internal exposure [C9]. During the temporary resettlement of Bikini Atoll from 1971 to 1978, total whole-body exposures were estimated to have been 2–3 mSv a^{-1} [G5]. A radiological survey of residual radiation levels, primarily due to global fallout deposition, was conducted throughout the Marshall Islands in 1994 [S2], and more detailed surveys have been made of Bikini and Enewetak atolls, in order to evaluate eventual permanent resettlement [I4, R1]. Estimated effective doses caused by residual contamination to persons who might return at present to Bikini Atoll were estimated to be 4 mSv with a diet composed of both local and imported foods and about 15 mSv for a diet of local origin only [I4]. Tests at other locations in the Pacific (Christmas Island and Johnston Island) were conducted in the high atmosphere, and there was little local fallout deposition.

(c) Semipalatinsk test site

71. The Semipalatinsk test site is located in the northeast corner of Kazakhstan (see map in Figure XIII). At this location, 456 nuclear tests were conducted, including 86 atmospheric and 30 surface tests [M2]. The most affected local populations lived mainly east and northeast of the test site, in the Semipalatinsk region of Kazakhstan and the Altai region of the Russian Federation. After some tests, traces of radioactive contamination were also formed in southern and southeastern directions [G8].

Figure XIII. Lop Nor and Semipalatinsk test sites.
The inner dotted circle indicates a distance of 500 km, the outer dashed circle 1,000 km from the test sites. The measurement areas in Gansu Province (for Lop Nor) and the Altai Region (for Semipalatinsk) are shown within elliptical areas.

72. Two tests were most significant in exposing the population of Kazakhstan: the first test on 29 August 1949 and the first thermonuclear test on 12 August 1953. These and two additional test (on 24 September 1951 and 24 August 1956) are stated in [G8] to have contributed 85% of the total collective effective dose from all tests. There are several

documents listing doses at specific locations for the population in Kazakhstan [G8, S7, T1], but the presented results differ markedly. Example results from the latest publication [S7] of accumulated effective doses for several districts indicate effective doses in the range from 0.04 to 2.4 Sv. The collective effective dose for ten districts is estimated to be 3,000–4,000 man Sv [S7]. The absorbed dose to the thyroid from the ingestion of radioiodines is quite uncertain, but is estimated to be as high as 8 Gy to children in the Akbulak settlement [S7].

73. The Altai region of the Russian Federation is about 200 km from the Semipalatinsk Test Site. This population experienced exposure following about 40 explosions [S8]. The most significant exposure was caused by the nuclear test of 29 August 1949 with other major exposures following tests on 3 September 1953, 1 August 1962, 4 August 1962, and 7 August 1962. Effective doses of about 2 Sv are estimated to have occurred in the Uglovski district following the 1949 test. The total collective dose to all residents in 58 districts with a total population of 1.9 million persons is estimated to be 42,000 man Sv [S8].

74. The results for Kazakhstan and the Altai region in the Russian Federation must at present be regarded with caution. There are significant discrepancies among the reported results for Kazakhstan, and the reported results for the Altai region differ markedly when derived from measured results or model calculations. Validation of results based upon contemporary measurements of ^{137}Cs deposition density might be useful in resolving some of these discrepancies.

75. Investigation of residual contamination levels at the Semipalatinsk site has begun. In 1993–1994, an international team performed a preliminary survey of the test site and surrounding area [I9]. More significantly contaminated areas were found at ground zero locations and surrounding Lake Balapan. Projected annual doses were estimated to be 10 mSv, mainly from external exposure, to individuals making daily visits to these sites and 100 mSv to those who might permanently reside at these locations. Present annual effective doses to persons living outside the test site boundaries were estimated to be of the order of 0.1 mSv from residual contamination levels.

(d) Novaya Zemlya test site

76. The test site Novaya Zemlya in the Russian Arctic is large and remote. Although an extensive atmospheric test programme was conducted there, most of the tests were carried out at high altitudes, thus minimizing local fallout. There was one test with a 32 kt yield on the land surface on 7 September 1957 [M2]. In addition, there were two tests on the surface of the water and three tests underwater at the site. Research programmes to investigate residual contamination both on- and off-site have been initiated. It may be that reindeer herders and those who consume reindeer meat received low internal exposures, primarily from ^{137}Cs, that could be attributed to tests at this site.

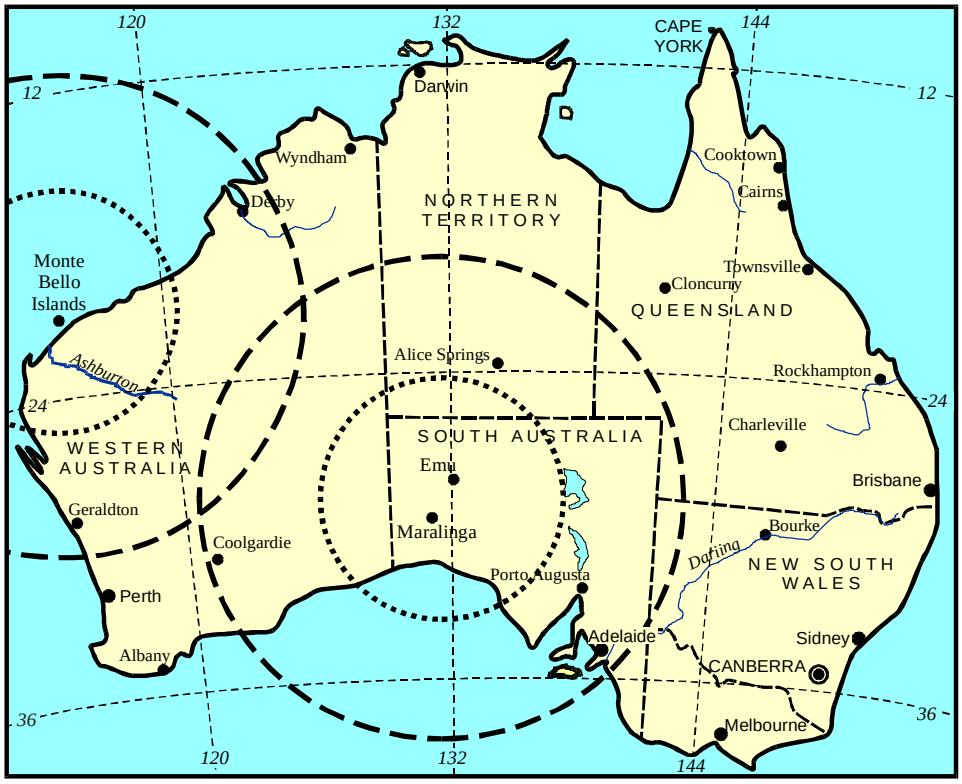


Figure XIV. Maralinga, Emu and Monte Bello test sites.
The inner dotted circle indicates a distance of 500 km, the outer dashed circle 1,000 km from the test sites.

(e) Maralinga, Emu test sites

77. The nuclear weapons testing programme of the United Kingdom included 21 atmospheric tests at sites in Australia and the Pacific. The tests in the Pacific at Malden and the Christmas Islands in 1957 and 1958 were airbursts over the ocean (six tests with submegatonne and megatonne yields) or explosions of devices suspended by balloons at 300–450 m over land (one test of 24 kt and two tests each with 25 kt yield) [D2]. Local fallout would have been minimal following those tests. Twelve tests were conducted from 1952 to 1957 at three sites in Australia: Monte Bello Islands, Emu, and Maralinga, which are shown on the map in Figure XIV. These were mainly surface tests with yields of 60 kt or less. For each of these tests, trajectories of the radioactive cloud were determined, and local and countrywide monitoring of air and deposition was performed [W1]. Estimates of external exposures in local areas were not made for the earlier tests; for the tests in 1956 and 1957, the external effective doses were less than 1 mSv [W1]. The sizes of local populations were not indicated. Estimates of internal exposures were also made for the entire Australian population. The average effective dose was 70 μSv, and the collective effective dose was 700 man Sv in this population [W1]. A number of safety tests were conducted at the Maralinga and Emu sites in South Australia, resulting in the dispersal of ^{239}Pu over some hundreds of square kilometres. The potential doses to local inhabitants of these areas have been evaluated [D1, H2, W3]. Following rehabilitation of the Maralinga test site it is estimated that potential doses to future inhabitants living a semi-traditional nomadic lifestyle will be less than 5 mSv [D1].

(f) Algerian, Mururoa, Fangataufa test sites

78. The French nuclear testing programme began with four low-yield surface tests at a site near Reggane in the Algerian Sahara in 1960 and 1961 [D3]. There is no information on local exposures following these tests. Some residual contamination remains at this site and at a nearby site, In Ecker, where 13 underground tests were conducted. Small quantities of plutonium were dispersed at these sites from safety experiments, which involved conventional explosives only. Investigations of the present radiation levels and potential exposures of individual who might utilize these areas have been initiated by the IAEA.

79. The subsequent programme of France was conducted at the uninhabited atolls of Mururoa and Fangataufa in French Polynesia in the South Pacific. Most of these tests involved the detonation of devices suspended from balloons at heights of 220–500 m [D3], limiting local fallout. Radiological monitoring has been conducted at surrounding locations. The closest inhabited atoll is Tureia (140 persons) at a distance of 120 km to the north; only 5,000 persons lived within 1,000 km of the test site. A larger population (184,000 persons in 1974) is located 1,200 km to the northwest, at Tahiti. Under the conditions that normally prevail at the test site, radioactive debris of the local and tropospheric fallout was carried to the east over uninhabited regions of the Pacific. On occasion, however, some material was transferred to the central South Pacific within a few days of the tests by westerly moving eddies. French scientists [B8] have identified five tests, following which regional population groups were more directly exposed (Table 19). A single rain-out event caused exposures in Tahiti after the test of 17 July 1974. Exposures resulted mainly from external irradiation from deposited radionuclides. Milk production on Tahiti is sufficient for only about 20% of local needs, and consumption is in any case low, which limited ingestion exposures. Estimated effective doses to maximally exposed individuals after all five events were in the range 1–5 mSv in the year following the test. A collective effective dose of 70 man Sv was estimated for all local exposures at this test site. Estimates of exposures were based on more extended measurements that were made beginning in 1982. In that year the external exposures in the region were in the range 1–10 μSv a^{-1}, internal exposures were 2–32 μSv a^{-1}, and total exposure was 3–33 μSv a^{-1}, due mostly to residual ^{137}Cs deposition from global fallout. The collective effective dose was estimated to be about 1 man Sv in 1982 for all of French Polynesia [R2]. An international investigation of the present radiological conditions at Mururoa and Fangataufa was conducted during 1996–1998 [I7]. Residual contamination levels were, on the whole, found to be negligibly low. Small areas with surface contamination from plutonium exist, but it was regarded as only remotely conceivable that a plutonium-containing particle could enter the body of an individual, e.g. through a cut in the skin. Plutonium, tritium, and caesium in the sediments of the lagoons were considered unlikely to cause non-negligible exposures at present or in the future to any repopulated individuals or to residents of other islands throughout the Pacific region [I7].

(g) Lop Nor test site

80. The Chinese nuclear weapons testing programme was carried out at the Lop Nor test site in western China, shown on the map in Figure XIII; 22 atmospheric tests were conducted between 1964 and 1980. Limited information is available on local deposition following the tests. Balloons were used to follow the trajectory of the debris clouds, and airborne and ground-based instruments were used to monitor the radiation levels. Estimates of exposures were made over a downwind area to a distance of 800 km [Z1]. Estimates of external exposures in cities or towns within 400–800 km of the test site in Gansu Province ranged from 0.02 to 0.11 mSv (Table 20), with an average of about 0.04 mSv for three tests, which accounted for over 90% of the dose from all Chinese tests [Z1]. Indoor occupancy of 80% and a building shielding factor of 0.2 were assumed. A retrospective dose evaluation based on soil sampling was conducted in 1987–1992 [R4]. The dose commitment from ^{137}Cs was estimated to range from 1.5 to 10 mSv in the northwest Ganzu province.

B. UNDERGROUND TESTS

81. Testing of nuclear weapons underground was begun in 1951 by the United States and in 1961 by the former Soviet Union. Following the limited nuclear test ban treaty

of 1963, which banned atmospheric tests, both countries conducted extensive underground test programmes. The United Kingdom participated with the United States in a few joint underground tests. The underground test programmes of France and China continued until 1996. India conducted a single underground test in 1974 and five further tests in 1998. Pakistan reported conducting six tests in 1998. A comprehensive test ban treaty was formulated in 1996, but it has not yet been ratified by all countries or entered into force. Thus, it cannot yet be said that the practice of underground weapons testing has also ceased.

82. The number of underground tests (Figure I, upper diagram) has greatly exceeded the number of atmospheric tests, but the total yield of the former (Figure I, lower diagram) has been much less. The largest underground tests had a reported yield of 1.5–10 Mt (27 October 1973, at Novaya Zemlya by the former Soviet Union) [M2] and less than 5 Mt (6 November 1971 at Amchitka, Alaska, by the United States) [D4], but most tests have been of a much lower yield, particularly if containment of nuclear debris was desired. Only with venting or diffusion of gases following the tests, as has happened on occasion, could local populations be exposed.

83. Underground test programmes were summarized in the UNSCEAR 1993 Report [U3] and the resultant exposures were estimated. No further information has become available that could allow exposure estimates to be improved. It would be desirable to have a more complete list of those tests in which venting occurred and estimates of the amounts of radioactive materials thereby dispersed in the atmosphere. Thirty-two underground tests conducted at the Nevada test site were reported to have led to off-site contamination as a result of venting [H3].

84. The number of underground tests requires revision, based on recently published information [D4, M2]. Several tests involved the simultaneous detonation of two or more nuclear charges, either in the same or in separate boreholes or tunnels. These so-called salvo tests were done for reasons of efficiency or economy, but they also deterred detection by distant seismic measurements. The tests usually involved two to four charges; the maximum number was eight. Since each charge has now been identified, they can be properly specified as separate tests. The annual numbers of underground tests conducted by each country are given in Table 21. The total number of tests by all countries is 1,876.

85. The yields of individual underground tests have not been directly specified. Many are simply reported to be within a range of energies, for example <20 kt or 20–150 kt. The annual yields of underground tests at all locations have been compiled by the National Defense Research Establishment in Sweden [N6]. These estimates were included in the UNSCEAR 1993 Report [U3]. The total yield of all tests conducted through 1992 was 90 Mt. The yields of subsequent tests have not altered this total amount. The total yield of all underground tests conducted by the former Soviet Union has been reported to be 38 Mt [M2]. The yields apportioned to other countries are listed in Table 22.

86. Table 22 provides a summary listing of all nuclear weapons tests, both atmospheric and underground. The total number of tests was 2,419; this includes the two combat explosions of nuclear weapons in Japan and a number of safety tests. The latter had no nuclear yield, but they are conventionally included in listings of nuclear tests. The total yield of all tests was 530 Mt.

C. PRODUCTION OF WEAPONS MATERIALS

87. In addition to weapons testing, the installations where nuclear materials were produced and weapons were fabricated were another source of radionuclide releases to which local and regional populations were exposed. Some information on this practice was presented in the UNSCEAR 1993 Report [U3]. Especially in the earliest years of this activity, the pressures to meet production schedules and the lack of stringent waste discharge controls resulted in higher local exposures than in the later years. Efforts are being made to evaluate the exposures that occurred during all periods in which these installations operated. Although it may not be possible to systematically evaluate all such exposures, newly acquired information is summarized in this Section. Also, at some sites, weapons are now being dismantled.

1. United States

88. Nuclear weapons plants in the United States included Fernald, in Ohio (materials processing); Portsmouth, in Ohio, and Paducah, in Kentucky (enrichment); Oak Ridge, in Tennessee (enrichment, separations, manufacture of weapons parts, laboratories); Los Alamos, in New Mexico (plutonium processing, weapons assembly); Rocky Flats, in Colorado (manufacture of weapons parts); Hanford, in Washington (plutonium production); and Savannah River, in South Carolina (plutonium production). There are many more sites at which such operations were conducted and wastes were stored or disposed. It has been estimated that there are some 5,000 locations in the United States where contamination by radioactive materials has occurred, not all of which are associated with weapons materials production [W4]. Estimates of releases of radioactive materials during the periods of operation of the nuclear installations are summarized in Table 23. Also listed are the exposures estimated to have been received by the local populations. This information might be extended when studies now underway are concluded, thus allowing better documentation of the historical exposures from this practice.

2. Russian Federation

89. There were three main sites where weapons materials were produced in the former Soviet Union: Chelyabinsk, Krasnoyarsk, and Tomsk. Relatively large routine releases

occurred during the early years of operation of these facilities. In additions, accidents have contributed to the background levels of contamination and to the exposure of individuals living in the local and regional areas.

(a) Chelyabinsk

90. The Mayak nuclear materials production complex is located in the Chelyabinsk region between the towns of Kyshtym and Kasli near the eastern shore of Lake Irtyash. Uranium-graphite reactors for plutonium production and a reprocessing plant began operating in 1948. Relatively large discharges of radioactive materials to the Techa River occurred from 1949 to 1956 [D5]. The available information on exposures to the local population was summarized in the UNSCEAR 1993 Report [U3].

91. Estimates of releases of radionuclides during the early years of operation of the Mayak complex are presented in Table 24. Controls of releases were introduced in the early 1960s. The maximum releases in airborne effluents, primarily ^{131}I, occurred from 1949 to 1956 [D6]. During the same period, the discharges of radionuclides into the Techa River occurred [D5, K3]. Of the 100 PBq released from 1949 to 1956, 95 PBq were released in 1950 and 1951. Along with the fission products listed in Table 24, plutonium isotopes were also released.

92. The individuals most highly exposed from the releases to the Techa River were residents of villages along the river, who used the water for drinking, fishing, waterfowl breeding, watering of livestock, irrigation of gardens, bathing, and washing. In April-May 1951, a heavy flood resulted in contamination of the flood plain used for livestock grazing and hay making. The collective dose to the most exposed population from 1949 to 1956 was 6,200 man Sv (Table 25). Doses from external irradiation decreased in 1956, when residents of the upper reaches of the river moved to new places and the most highly contaminated part of the flood plain was enclosed. For some inhabitants, however, the Techa River contamination remains a significant source of exposure up to the present time.

93. On 29 September 1957, a fault in the cooling system of a storage tank containing liquid radioactive wastes led to a chemical explosion and a large release of radionuclides. The total activity dispersed off-site over the territory of the Chelyabinsk, Sverdlovak, and Tyumen regions was approximately 74 PBq. The composition of the release is indicated in Table 24. Although the release was characterized mainly by rather short-lived radionuclides (^{144}Ce, ^{95}Zr), the long-term hazard was due primarily to ^{90}Sr. An area of 23,000 km^2 was contaminated at levels of ^{90}Sr greater than 3.7 kBq m^{-2} [N8]. In 1957, 273,000 people lived in the contaminated area. Of them, 10,000 lived where the ^{90}Sr deposition density exceeded 74 kBq m^{-2} and 2,100 where the levels were over 3,700 kBq m^{-2}. In areas where ^{90}Sr contamination exceeded 74 kBq m^{-2}, the population was evacuated, and relocated first from the most severely affected area within 7–10 days and the remaining population over the next 18 months. The main pathways of exposure following the accident were external irradiation and internal exposure from the consumption of local food products.

94. The Mayak complex was responsible for further exposure of the local population in 1967, when water receded from Lake Karachy, which had been used for waste disposal, and the wind resuspended contaminated sediments from the shoreline. The dispersed material, about 0.022 PBq, consisted mainly of ^{137}Cs, ^{90}Sr, and ^{144}Ce (Table 24). The contaminated area, defined as having levels of ^{90}Sr greater than 3.7 kBq m^{-2} and of ^{137}Cs greater than 7.4 kBq m^{-2}, extended 75 km from the lake. Approximately 40,000 people lived within this area of 2,700 km^2. The exposures from external irradiation and the consumption of local foods were considerably less than those following the 1957 storage tank accident.

95. Present levels of exposure associated with operation of the Mayak complex have been estimated from the residual contamination [K4]. For internal exposure, the average (and range) of daily consumption of food were determined to be milk 0.7 (0.5–1.0) kg, meat 0.14 (0.09–0.18) kg, bread 0.36 (0.27–0.52) kg, potatoes 0.57 (0.2–1.0) kg, vegetables 0.24 (0.14–0.43) kg, fish 0.05 (0.03–0.11) kg, mushrooms 0.02 (0.01–0.03) kg, and berries 0.04 (0.01–0.06) kg [K4]. These values were used with the concentrations given in Table 26 to estimate the average annual dose from internal exposure of 100 μSv. Average annual dose from external exposure is estimated to be 10 μSv. For the population of 320,000 surrounding the Mayak complex, the annual collective effective dose from present operations (1993–1996) is estimated to be 35 man Sv (Table 27).

(b) Krasnoyarsk

96. The Krasnoyarsk nuclear materials production complex is located about 40 km from the city of Krasnoyarsk. The first two reactors at Krasnoyarsk were direct-flow type commissioned in 1958 and 1961. A third, closed-circuit reactor, was commissioned in 1964. A radiochemical plant for irradiated fuel reprocessing began operation in 1964. In 1985, a storage facility for spent fuel assemblies from reactors in the Soviet republics of Russia and Ukraine was put into service. There are plans to reprocess this fuel from the civilian nuclear fuel cycle in the future at the Krasnoyarsk site.

97. Radioactive wastes discharges from the Krasnoyarsk complex enter the Yenisei River. Trace contamination can be found from the complex to the estuary, about 2,000 km away [V1]. An estimate of the collective dose from radioactive discharges of the Krasnoyarsk complex during 1958–1991 is presented in Table 25 [K5]; the estimate is derived from data on the content of radionuclides in water, fish, flood plain, and other components of the river ecosystem [N9, V1]. On the whole, the collective dose was about 1,200 man Sv. The most important contributor (70%) to this dose was fish consumption [K6]. External exposure from the contaminated flood plain accounted for 17% of the collective dose. The main radionuclides contributing to the internal dose from fish consumption were ^{32}P, ^{24}Na, ^{54}Mn, and ^{65}Zn. The main contributor to

the external dose (over 90%) was gamma-emitting radionuclides, primarily ^{137}Cs, ^{60}Co, and ^{152}Eu. Individual doses to the population varied over a wide range, from 0.05 to 2.3 mSv a^{-1}. The main portion of the collective dose (about 84%) was received by the population living within 350 km of the site of the radioactive discharges.

98. In 1992, the direct-flow reactors of the Krasnoyarsk complex were shut down. This considerably reduced the amount of radioactive discharges to the Yenisei River, and the annual collective dose to the population was decreased by a factor of more than 4. Present estimates of average doses (1993–1996) are 30 µSv a^{-1} (external) and 20 µSv a^{-1} (internal). With a local population of 200,000, the annual collective effective dose is estimated to be 10 man Sv (Table 27).

(c) Tomsk

99. The Siberian nuclear materials production complex is located in the town of Tomsk-7 on the right bank of the Tom River 15 km north of the city of Tomsk. The Siberian complex was commissioned in 1953. It is the largest complex for the production of plutonium, uranium, and transuranic elements in the Russian Federation. The Siberian complex includes five uranium-graphite production reactors that began operation in 1958–1963, enrichment and fuel fabrication facilities, and a reprocessing plant [B7].

100. Radionuclides in liquid wastes are discharged into the Tom River, which flows into the Ob River. An estimate of the collective dose from radioactive discharges of the Siberian complex from 1958 to 1992 is presented in Table 25. The exposure pathways considered in the dose evaluation were the ingestion of fish, drinking water, waterfowl, and irrigated products and external exposure from the contaminated flood plain. The collective effective dose was estimated to be 200 man Sv. The largest contributor (73%) to this dose was fish consumption. The main radionuclides contributing to the internal dose from fish consumption were ^{32}P and ^{24}Na. The largest portion of the collective dose (about 80%) was received by the population living within 30 km of the site of radioactive discharges.

101. In 1990–1992, three of the five reactors of the Siberian complex were shut down. This considerably reduced the amount of radioactive discharges to the Tom River and the annual collective dose to the population. The average annual doses to the local population are estimated to be 0.4 µSv (external) and 5 µSv (internal). For the local population of 400,000, the collective effective dose at present (1993–1996) is estimated to be 2.2 man Sv (Table 27).

102. On 6 April 1993, an accident occurred at the radiochemical plant of the Siberian complex that resulted in the release of radioactive materials [B7, G6, I6]. A narrow trace of radioactive contamination 35–45 km long was formed in a northeasterly direction from the complex (based on trace concentrations of ^{95}Zr and ^{95}Nb in soil). The total area of the contamination with dose rate levels at the time of the accident higher than the natural radiation background was estimated to be about 100 km^2 [M8]. The dominant radionuclides in snow samples from the contaminated area were ^{95}Zr, ^{95}Nb, ^{106}Ru, and ^{103}Ru. Traces of ^{239}Pu and ^{144}Ce were also detected. A non-uniformity of contamination was noted, with the presence of hot particles in the composition of radioactive materials deposited on the snow. There are no populated places in the area of the pattern, except for the village of Georgievka, which has a population of 73 persons (including 18 children). The cumulative dose from external exposure to the inhabitants of Georgievka from the accident during 50 years of permanent residence will amount to 0.2–0.3 mSv [B7], which is negligible, compared to the dose from natural background radiation over the same period.

3. United Kingdom

103. The production of nuclear materials and the fabrication of weapons began in the 1950s in the United Kingdom. The work was carried on for several years at sites such as Springfields (uranium processing and fuel fabrication), Capenhurst (enrichment), Sellafield (production reactors and reprocessing), Aldermaston (weapons research), and Harwell (research). Subsequently, work related to the commercial nuclear power programme was incorporated at some of these sites. In the earliest years of operation of these installations, the radionuclide discharges may be associated almost wholly with the military fuel cycle.

104. Plutonium production reactors were operated in the United Kingdom at Sellafield (two graphite-moderated, gas-cooled reactors known as the Windscale piles) and, later, at Calder Hall on the Sellafield site and Chapelcross in Scotland. A fire occurred in one of the Windscale reactors in 1957, resulting in the release of radionuclides, most notably ^{131}I, ^{137}Cs, ^{106}Ru, ^{133}Xe, and ^{210}Po. The prompt imposition of a ban on milk supplies in the affected region reduced exposures to ^{131}I. The collective effective dose from the accident was estimated to be 2,000 man Sv.

4. France

105. A nuclear programme in France began in 1945 with the creation of the Commissariat à l'Energíe Atomique (CEA). The nuclear research laboratory at Fontenay-aux-Roses began activities in the following year. The first experimental reactor, named EL1 or Zoé, went critical in 1948, and a pilot reprocessing plant began operation in 1954. A second experimental reactor, EL2, was constructed at the Saclay centre. From 1956 to 1959, three larger production reactors began operation at the Marcoule complex on the Rhône River. These gas-cooled, graphite-moderated reactors, designated G1, G2, and G3, operated until 1968, 1980, and 1984. A full-scale reprocessing plant, UP1, was built and operated from 1958, also at the Marcoule site. Two more plants to reprocess fuel from commercial reactors were constructed at La Hague in the north of France: UP2, completed in 1966, and UP3, in 1990.

106. Although some systematic reporting of radionuclide discharge data is available beginning in 1972 [C10], some

of this may reflect the reprocessing of commercial reactor fuel. It should be possible to estimate plutonium production amounts at the various installations, and some reports of environmental monitoring (e.g. [M9]) may give indications of early operating experience.

5. China

107. A nuclear weapons development programme was initiated in China that led to the first nuclear explosion of that country, conducted in 1964. The Institute of Atomic Energy was created in 1950. The first experimental reactor was constructed in Beijing, and a uranium enrichment plant was built at Lanzhou in Ganzu Province in western China. The first nuclear test was of an enriched uranium device. Plutonium production and reprocessing were conducted at the Jiuquan complex, also located in Ganzu Province. The production reactor began operation in 1967 and the reprocessing plant in 1968. Production and reprocessing also occurred in Guangyuan in Sichuan Province, where larger installations were constructed. The weapons were assembled at the Jiuquan complex.

108. Assessment of exposures from nuclear weapons production in China have been reported by Pan et al. [P4, P5, P6]. Exposures to populations surrounding specific installations were estimated. This experience relates to the military fuel cycle, since the commercial nuclear power programme started only in the last decade.

II. NUCLEAR POWER PRODUCTION

109. The Committee has routinely collected data on releases of radionuclides from the operation of nuclear fuel cycle installations. In the UNSCEAR 1993 Report [U3], an overview was provided of annual releases of radionuclides for the general types of reactors and other fuel cycle installations since the beginning of the practice of commercial nuclear power generation. Data for individual mines, mills, reactors, and reprocessing plants were given for the years 1985–1989. In this Annex, the data for another five-year period, 1990–1994, and a three-year period, 1995–1997, are assessed.

110. The generation of electrical energy by nuclear means has grown steadily from the start of the industry in 1956. The relatively rapid rate of expansion that occurred from 1970 to 1985, an increase in energy generation of more than 20% per year, slowed to a pace averaging just over 2% per year from 1990 to 1996 [I1]. At the end of 1997, there were 437 nuclear reactors operating in 31 countries. The total installed capacity was 352 GW, and the energy generated in 1997 was 254 GW a [I1]. It is projected [I1] that nuclear energy will continue to supply about 17% of the total electrical energy generated in the world, as at present, or possibly a few percent less.

111. The nuclear fuel cycle includes the mining and milling of uranium ore and its conversion to nuclear fuel material; the fabrication of fuel elements; the production of energy in the nuclear reactor; the storage of irradiated fuel or its reprocessing, with the recycling of the fissile and fertile materials recovered; and the storage and disposal of radioactive wastes. For some types of reactors, enrichment of the isotopic content of ^{235}U in the fuel material is an additional step in the fuel cycle. The nuclear fuel cycle also includes the transport of radioactive materials between the various installations.

112. Radiation exposures of members of the public resulting from discharges of radioactive materials from installations of the nuclear fuel cycle were assessed in previous UNSCEAR reports [U3, U4, U6]. In this Annex, the trends in normalized releases and the resultant doses from nuclear reactor operation are presented for the years 1970–1997. The doses are estimated using the environmental and dosimetric models described in Annex A, "*Dose assessment methodologies*".

113. The doses to the exposed individuals vary widely from one installation to another, between different locations and with time. Generally, the individual doses decrease markedly with distance from a specific source. To evaluate the total impact of radionuclides released at each stage of the nuclear fuel cycle, the results are evaluated in terms of collective effective dose per unit electrical energy generated, expressed as man Sv $(GW\,a)^{-1}$. Only exposures to members of the public are considered in this Annex. Occupational exposures associated with nuclear power production are included in Annex E, "*Occupational radiation exposures*".

A. MINING AND MILLING

114. Uranium mining involves the removal from the ground of large quantities of ore containing uranium and its decay products. Underground and open-pit mining are the main techniques. Underground mines produced 40% of the world´s total uranium production in 1996 and open-pit mines, 39% [O1]. Uranium is also mined using *in situ* leaching, which produced 13% of the world uranium in 1996 [O1]. The remaining 8% was recovered as a by-product of other mineral processing. Milling operations involve the processing of the ore to extract the uranium in a partially refined form, known as yellowcake.

115. Uranium mining and milling operations are conducted in several countries. Production in recent years is given in Table 28. In 1997 about 90% of world uranium production took place in 9 countries: Australia, Canada, Kazakhstan, Namibia, Niger, the Russian Federation, South Africa, the United States, and Uzbekistan. It is noted that oversupply, leading to large stockpiles and low prices,

has led to considerable reductions in output since 1989 [O1]. However, beginning in 1995, production of uranium was substantially increased in some countries, mainly Australia, Canada, Namibia, Niger, and the United States. The world production in 1997 was 35,700 t uranium.

1. Effluents

116. There are few new data on releases of radionuclides, mainly radon, in mining and milling operations. Limited data for underground mines, based on concentrations in exhaust air, were given in the UNSCEAR 1993 Report [U3] for Australia, Canada, and Germany. There were no estimates of releases in open-pit operations. For underground mines the release of radon, normalized to the production of uranium oxide (U_3O_8), ranged from 1 to 2,000 GBq t^{-1}, with a production-weighted average of 300 GBq t^{-1}. Based on the estimated uranium (fuel) requirements for the reactor types presently in use, 250 t uranium oxide are required to produce 1 GW a of electrical energy [U3]. This leads to an average normalized radon release from mines of approximately 75 TBq $(GW\ a)^{-1}$.

117. In the UNSCEAR 1993 Report [U3], the average normalized radon release from mills in Australia and Canada, also from the limited data available, was estimated to be 3 TBq $(GW\ a)^{-1}$ [U3]. These values are not expected to change with current mining and milling practices. For mining operations in arid areas, liquid effluents are minimal, and radionuclide releases via this pathway are estimated to be of little consequence.

118. The mining and milling processes create various waste residues in addition to the uranium product. The tailings consist of the crushed and milled rock from which the mineral has been extracted, together with any chemicals and fluids remaining after the extraction process. The long-lived precursors of ^{222}Rn, namely ^{226}Ra (half-life 1,600 a) and ^{230}Th (half-life 80,000 a), present in the mill tailings provide a long-term source of radon release to the atmosphere. Based on available data, the radon emission rates were estimated in the UNSCEAR 1993 Report [U3] to be 10 Bq s^{-1} m^{-2} of tailings during the operational phase of the mill (assumed to be five years) and 3 Bq s^{-1} m^{-2} from abandoned but stabilized tailings (assumed period of unchanged release of 10,000 years). Assuming that the production of a mine generates about 1 ha $(GW\ a)^{-1}$, the normalized radon releases are 3 and 1 TBq $(GW\ a)^{-1}$ for the operational and abandoned tailings, respectively. The *in situ* leach facilities have no surface tailings and little radon emissions after closure. Release estimates from mining and milling operations are summarized in Table 29.

119. In a recent study of eight major uranium production facilities in Australia, Canada, Namibia, and Niger [S6], measured emission rates were reported to range from background to 35 Bq s^{-1} m^{-2} from the tailings of presently operating mills. Following decommissioning, the release rates are at present or are expected to be no more than 7 Bq s^{-1} m^{-2} [S6]. For many of the uranium mill tailings, the long-term management involves substantial water-saturated cover, which reduces the radon emission rate to 0–0.2 Bq s^{-1} m^{-2}. Taking into account present tailings areas yet to be rehabilitated with good present techniques and the anticipated future practice, the emission rate from abandoned mill tailings can be assumed to be less than 1 Bq s^{-1} m^{-2}. This value is adopted for the present evaluation. The previous estimate was 3 Bq s^{-1} m^{-2} [U3]. For comparison, the average emission rate corresponding to soils in normal background areas is 0.02 Bq s^{-1} m^{-2} [U3].

2. Dose estimates

120. The methodology used by the Committee to estimate the collective dose from mining and milling is described in the UNSCEAR 1977 and 1982 Reports [U4, U6]. The dose estimate is based on representative release rates from a model mine and mill site having the typical features of existing sites. An air dispersion model is used to estimate the radon concentrations from releases as a function of distance from the site, and the most common environmental pathways are included to estimate dose. Thus, the results are not applicable to any given site without duly considering site-specific data but are meant to reflect the overall impact of mining and milling facilities.

121. The previously estimated exposures for the model mine and mill site assumed population densities of 3 km^{-2} at 0–100 km and 25 km^{-2} at 100–2,000 km. The collective effective dose factor for atmospheric discharges in a semi-arid area with an effective release height of 10 m was 0.015 man Sv TBq^{-1} [U3], based on the dose coefficient for radon of 9 nSv h^{-1} per Bq m^{-3} (EEC). As the dilution factor at 1 km has been reduced from 3 10^{-6} to 5 10^{-7} s m^{-3}, the dose per unit release of radon becomes 0.0025 man Sv TBq^{-1}. Using this factor, the collective effective dose per unit electrical energy generated is estimated to be 0.2 man Sv $(GW\ a)^{-1}$ during operation of the mine and mill and 0.00075 man Sv $(GW\ a)^{-1}$ per year of release from the residual tailings piles. For the assumed 10,000-year period of constant, continued release from the tailings, the normalized collective effective dose becomes 7.5 man Sv $(GW\ a)^{-1}$ (Table 29). The various revisions in the parameters have led to a considerable reduction from the previously estimated value of 150 man Sv $(GW\ a)^{-1}$ [U3].

122. An alternative assessment of exposures from mill tailings has been proposed in a study prepared for the Uranium Institute [S6]. In this study, site-specific data relating to currently operating mills in four countries (Australia, Canada, Namibia, and Niger) were utilized. Differences from the UNSCEAR results arise from the use of a more detailed dispersion model, much-reduced population densities (<3 km^{-2} within 100 km and from 2 to 7 km^{-2} in the region between 100 and 2,000 km), and more ambitious future tailings management with substantial covers to reduce radon emissions. The overall result (adjusting for the radon dose coefficient of 9 nSv h^{-1} per Bq m^{-3}, as used above) is 1.4 man Sv $(GW\ a)^{-1}$ over a 10,000-year

period, which although less by a factor of 5, it is in reasonable agreement with the estimate derived in the previous paragraph.

123. In France, exposures from mill tailings at Lodeve mining site were assessed considering measurements of radon releases prior to and after remediation [T6]. Calculations were based on a Gaussian plume dispersion model, and actual population densities of 63 km^{-2} at 0–100 km and 44 km^{-2} at 100–2,000 km were used. Before remediation the average measured flux was found to be 28 Bq m^{-2} s^{-1}. The average annual effective dose to individuals within 10 km from the tailings was assessed to be about 20 μSv. Considering that 12,850 tonnes of uranium were extracted during the whole duration of processing, the collective effective dose to the population living within 2,000 km of the tailings and over a period of 10,000 years was estimated to be 380 man Sv $(GWa)^{-1}$. This value is much higher than the estimate of the previous paragraph, which is due to higher radon fluxes and population densities and to the different atmospheric dispersion model. After remediation of the site, the radon fluxes were found not to be different from the background, and the collective dose was assess to be almost zero.

124. For the model mining and milling operations, the annual release of radon is of the order of 80 TBq $(GW\ a)^{-1}$ (Table 29). With annual average production of 4,000 t in the main producing countries (Table 28: 36,000 t mostly from 9 countries) and assuming the collective dose is received by the population within 100 km from the mine and mill sites (3 km^{-2} to 100 km = 90,000 persons), the annual dose is estimated to be about 40 μSv [4,000 t ÷ 250 t $(GW\ a)^{-1}$ × 80 TBq $(GW\ a)^{-1}$ × 0.0025 man Sv TBq^{-1} ÷ 90,000 persons]. This dose rate would be imperceptible from variations of the normal background dose rate from natural sources.

125. The Committee recognizes that considerable deviations are possible from the representative values of parameters selected for the more general conditions of present practice. For example, much higher population densities are reported in areas surrounding the mills in China [P4], and previously abandoned tailings may not have been so carefully secured as is evidently possible. Although careful management of tailings areas would be expected in the future, the extremes of leaving the tailings uncovered to providing secure and covered impoundment could increase or decrease the estimated exposure by at least an order of magnitude. Further surveys of site-specific conditions would be useful to establish realistic parameters for the worldwide practice.

B. URANIUM ENRICHMENT AND FUEL FABRICATION

126. For light-water-moderated and -cooled reactors (LWRs) and for advanced gas-cooled, graphite-moderated reactors (AGRs), the uranium processed at the mills needs to be enriched in the fissile isotope ^{235}U. Enrichments of 2%–5% are required. Before enrichment, the uranium oxide (U_3O_8) must be converted to uranium tetrafluoride (UF_4) and then to uranium hexafluoride (UF_6). Enrichment is not needed for gas-cooled, graphite-moderated reactors (GCRs) or heavy-water-cooled and -moderated reactors (HWRs).

127. In fuel fabrication for LWRs (PWRs and BWRs) and AGRs, the enriched UF_6 is chemically converted to UO_2. The UO_2 powder is sintered, formed into pellets, and loaded into tubes (cladding) of Zircaloy and stainless steel, which are sealed at both ends. These fuel rods are arranged in arrays to form the reactor fuel assemblies. The fuel pins for HWRs are produced from natural uranium or slightly enriched uranium sintered into pellets and clad in zirconium alloy. The natural uranium metal fuel for GCRs is obtained by compressing the UF_4 with shredded magnesium and heating. The reduced uranium is cast into rods that are machined and inserted into cans.

128. The releases of radioactive materials from the conversion, enrichment, and fuel fabrication plants are generally small and consist mainly of uranium series isotopes. Available data from operating installations were reported in the UNSCEAR 1993 Report [U3]. For the model installations, the normalized collective effective dose from these operations was estimated to be 0.003 man Sv $(GW\ a)^{-1}$. Inhalation is the most important exposure pathway. The collective doses from liquid discharges comprise less than 10% of the total exposure.

C. NUCLEAR REACTOR OPERATION

129. The reactors used for electrical energy generation are classified, for the most part, by their coolant systems and moderators: light-water-moderated and -cooled pressurized or boiling water reactors (PWRs, BWRs), heavy-water-cooled and -moderated reactors (HWRs), gas-cooled, graphite-moderated reactors (GCRs), and light-water-cooled, graphite-moderated reactors (LWGRs). These are all thermal reactors that use the moderator material to slow down fast fission neutrons to thermal energies. In fast breeder reactors (FBRs), there is no moderator, and the fission is induced by fast neutrons; the coolant is a liquid metal. FBRs are making only minor contributions to energy production. The electrical energy generated by these various types of reactors from 1970 through 1997 is illustrated in Figure XV and the data since 1990 for individual reactor stations are given in Table 30 [I3].

130. The Committee derives average releases of radionuclides from reactors based on reported data, and these averages are used to estimate the consequent exposures for a reference reactor. Mathematical models for the dispersion of radionuclides in the environment are used to calculate, for each radionuclide or a combination of radionuclides, the doses resulting from released activity. The geographical location of the reactor, the release points, the distribution of the population, food production and consumption habits, and the

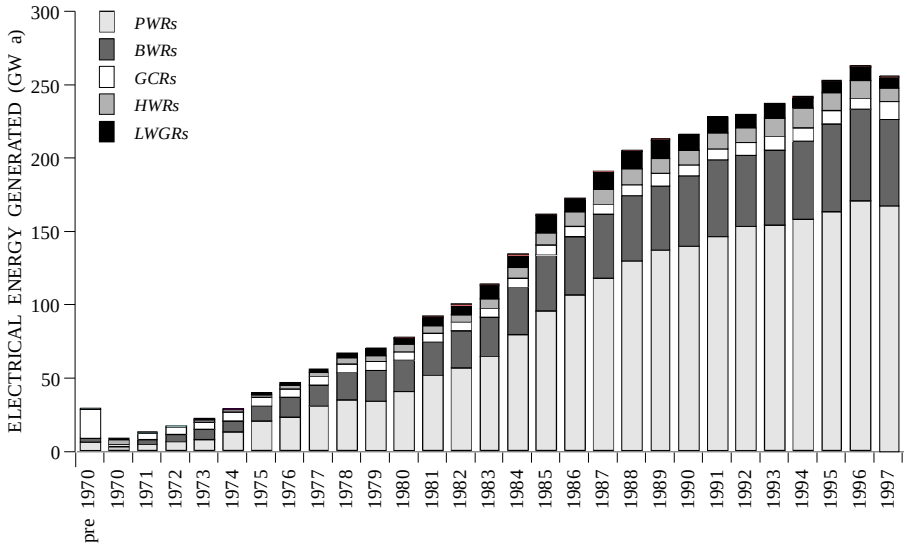


Figure XV. Contributions by reactor type to total electrical energy generated worldwide by nuclear means.

environmental pathways of radionuclides are factors that influence the calculated dose. The same release of activity and radionuclide composition from different reactors can give rise to different radiation doses to the public. Thus, the calculated exposures for a reference reactor provide only a generalized measure of reactor operating experience and serve as a standardized parameter for analysing longer-term trends from the practice.

1. Effluents

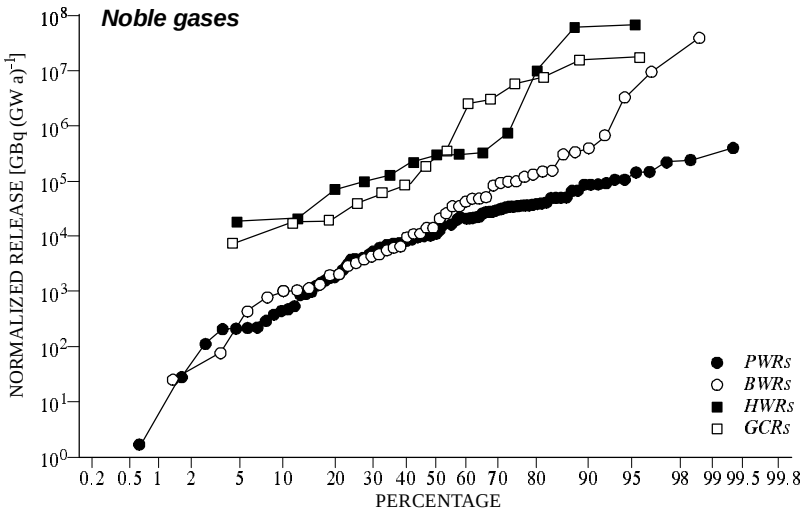
131. The radioactive materials released in airborne and liquid effluents from reactors during routine operation are reported with substantial completeness. The data for 1990–1997 are included in Tables 31–36: noble gases in airborne effluents (Table 31), tritium in airborne effluents (Table 32), iodine-131 in airborne effluents (Table 33), particulates in airborne effluents (Table 34), tritium in liquid effluents (Table 35), and radionuclides other than tritium in liquid effluents (Table 36). Each table also includes a summary of the total releases and the normalized releases (amount of radionuclide released per unit electrical energy generated) for each year of the five-year period 1990–1994 and for the three-year period 1995–1997 for each type of reactor and for all reactors together. Average normalized releases of radionuclides from each reactor type in five-year periods beginning in 1970 and for the three-year period 1995–1997 are presented in Table 37.

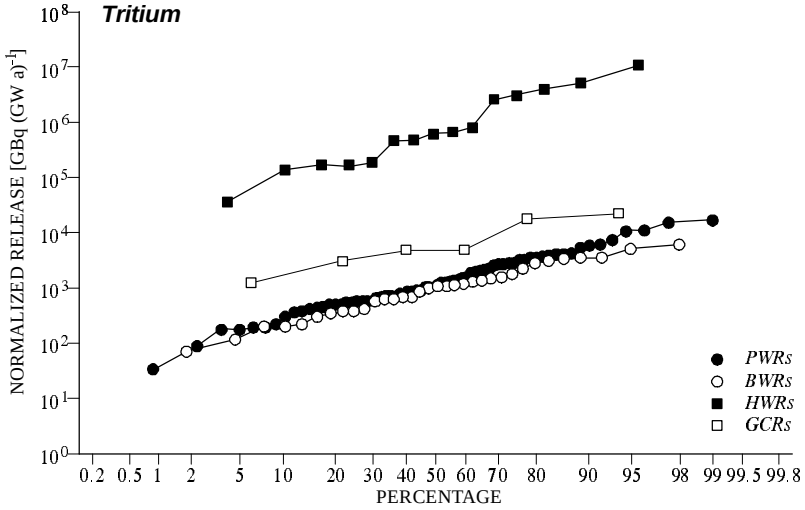
132. The normalized releases have traditionally been compiled for each reactor type. This is justified by the different composition of the releases, e.g. for noble gases, ^{41}Ar from GCRs and krypton and xenon isotopes from other types of reactors. In this case, different dose factors are required to estimate the doses. For other release components, e.g. ^{14}C or ^{131}I, there may be no inherent differences between reactor types, and atypical releases from one or a few reactors may dominate the normalized release values. In this case, the average normalized releases reflect only the prevailing operating experience, which cannot be taken as representative of the releases from a particular reactor type. With relatively complete data, little extrapolation is needed for estimating the collective doses from the total releases, and the normalized values are retained by reactor type mainly for convenience.

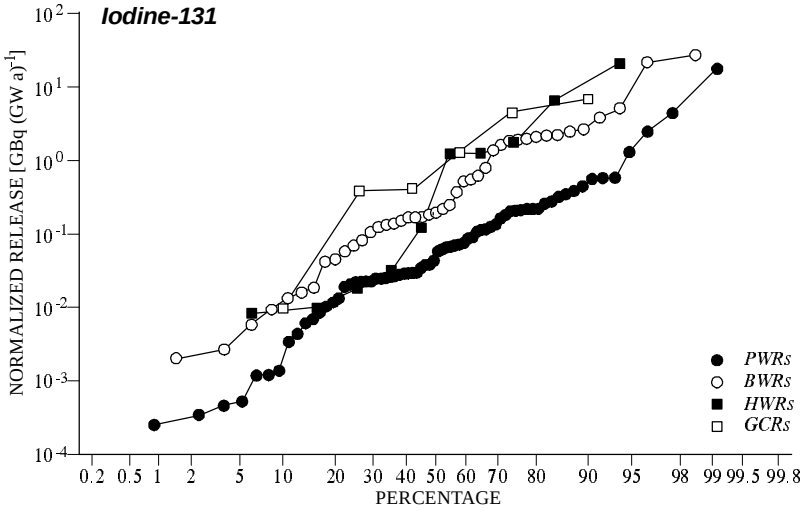
133. The release experience of individual reactors during the last five-year period (1990–1994) is evaluated in Figure XVI and shown as the characteristic distributions of the different reactor types. All reactors with relatively complete entries in Tables 31–36 (four or five years of data for both release amount and energy generated) are included in the figures. Each point has been derived from the total release of the radionuclide in 1990–1994 divided by the electrical energy generated in the same period. This evaluation of normalized release partly eliminates variations in annual values during the five-year period. There are, however, substantial differences in values from one reactor to another. Some factors affecting releases of radionuclides include the integrity of the fuel, the waste management systems, and procedures and maintenance operations conducted during the period of interest.

134. To obtain the characteristic distribution diagrams, the data are put in ranked order. The cumulative fractional value of point i of n points is specified as i/(n + 1). The inverse of the standard normal cumulative distribution of each fractional point is then derived. The value expresses the standard deviation of the data point from the centre of the distribution. In Figure XVI, the abscissa has been transformed to a percentage scale (0 = 50%, 1 SD = 84.14%, 2 SD = 97.73%, etc.). With a logarithmic scale on the ordinate, a straight line indicates a log-normal distribution. A steep slope indicates wide variations in the data. Breaks in the line indicate separate subpopulations of the available data. Outlier points are readily identified in these plots.

135. The distribution of normalized releases from reactors are approximately log-normal, often with a wide distribution of the data. The normalized releases of noble gases (Figure XVI) span seven orders of magnitude. There may be some differences in the composition of noble gases reported in airborne effluents, particularly the short-lived isotopes. The


Noble gases
NORMALIZED RELEASE [GBq (GW a)-1]
PERCENTAGE
PWRs
BWRs
HWRs
GCRs


Tritium
NORMALIZED RELEASE [GBq (GW a)-1]
PERCENTAGE
PWRs
BWRs
HWRs
GCRs


Iodine-131
NORMALIZED RELEASE [GBq (GW a)-1]
PERCENTAGE
PWRs
BWRs
HWRs
GCRs

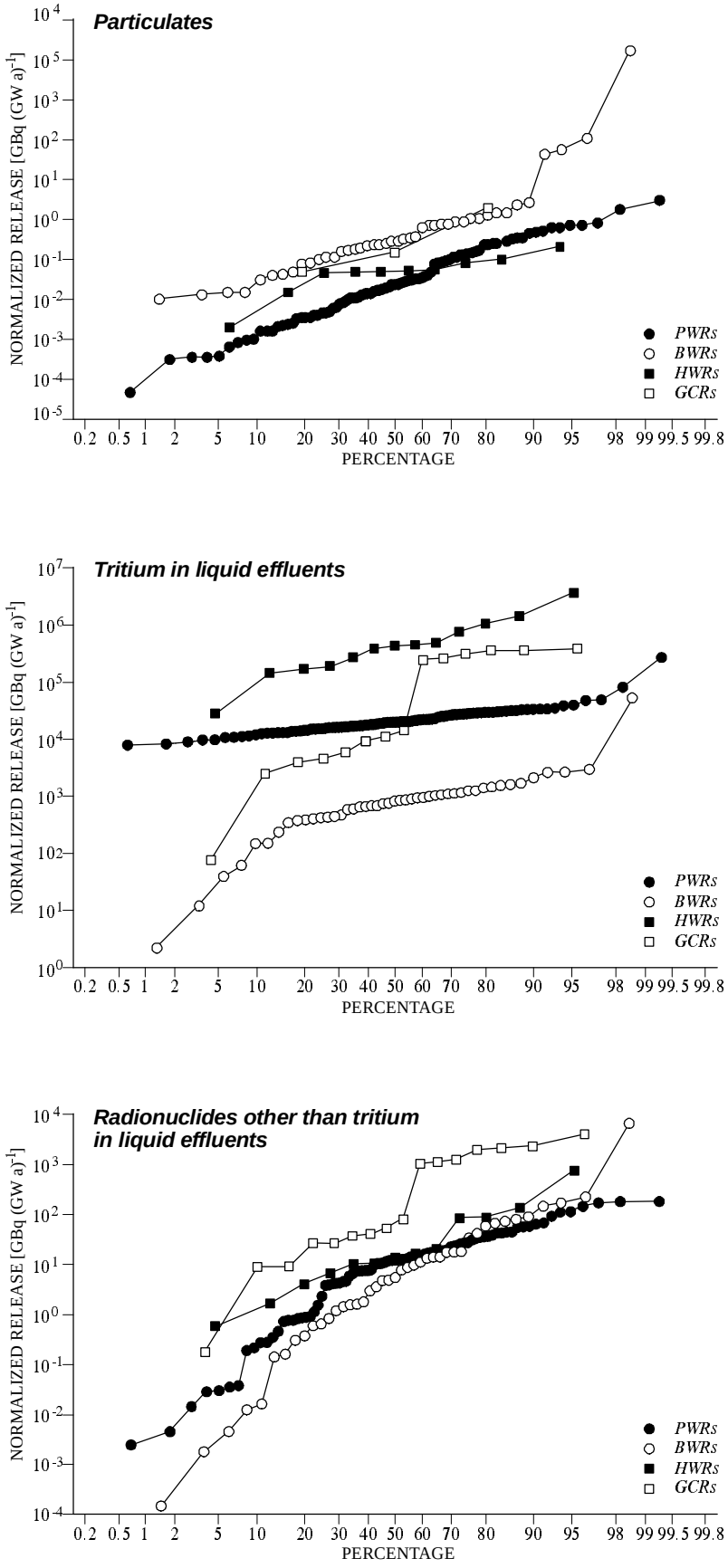


Figure XVI. Normalized release of noble gases, tritium, iodine-131 and particulates in airborne effluents and tritium and other radionuclides in liquid effluents from reactors during 1990–1994.

distributions for PWRs and BWRs are similar, but with deviations to higher normalized releases from BWRs in the upper range of the distribution. The highest values for BWRs are from the reactors Big Rock Point, Ringhals 1, and Tarapur 1–2, ranging from 3,400 to 41,000 TBq (GW a)$^{-1}$. The mean value for all BWRs is 18 TBq (GW a)$^{-1}$. The distributions for GCRs and HWRs are similar and somewhat higher than those for PWRs and BWRs.

136. The normalized releases of tritium in airborne effluents (Figure XVI) are less wide ranging. The distributions for PWRs and BWRs are identical; the distribution for GCRs is somewhat higher, with fewer values available, however. The distribution for HWRs is much higher, reflecting the large amounts of tritium produced in the moderator of these reactors. Among HWRs, those in Canada and the reactors Fugen, Embalse, and Wolsong 1 are all below 800 TBq (GW a)$^{-1}$, while Karachi, Atucha 1, and the Indian reactors are at higher values.

137. The distribution of ^{131}I releases in airborne effluents (Figure XVI) are quite wide and are somewhat higher for BWRs and HWRs than for PWRs. There are fewer values for GCRs; however, when several reactors with data for three years in 1990–1994 are included, the distribution is similar to that of BWRs and HWRs.

138. The distributions of particulate releases are also shown in Figure XVI. The strikingly high values in Table 34 for the Swedish BWR Ringhals 1 in 1994 and 1995 are attributable to damage in fuel elements beginning in 1993 and a problem in delaying releases of radionuclides entering turbine room air [N3]. These releases were to a large extent due to rather short-lived nuclei. Nuclei with half-lives of less than 83 minutes gave rise to 98% of the released activity. Authorized discharge limits were not exceeded; the atmospheric releases reached a maximum of 36% of the total dose limit for individuals (0.1 mSv a^{-1}) of the hypothetical critical group. The average value for 1990–1994 for this reactor [17 TBq (GW a)$^{-1}$] is the highest in the distribution for BWRs (Figure XVI). Relatively high values [0.04–0.1 TBq (GW a)$^{-1}$] were also derived for the BWRs Forsmark 1–3, Tarapur 1–2, and Oskarshamn 1–3. The distributions of particulate releases are very different for the different reactor types and are somewhat higher for BWRs and GCRs than for PWRs.

139. Normalized releases of tritium in liquid effluents (Figure XVI) are fairly uniform about the mean values for most of the reactors. The distribution for BWRs is lowest and for HWRs, highest. Intermediate are the distributions for PWRs and GCRs. The mean value for the group is about 1 TBq (GW a)$^{-1}$. The GCRs seem to form two distributions, with newer reactors at the higher end and the older reactors at the lower end, the opposite of the case for the noble gas releases. The HWRs are gathered about a mean normalized release of tritium in liquid effluents of about 400 TBq (GW a)$^{-1}$; at the lower extreme is the Pickering 5–8 station [28 TBq (GW a)$^{-1}$] and at the higher end [1,100–3,700 TBq (GW a)$^{-1}$] are Bruce 1–4, Kalpakkam 1–2, and Atucha 1.

140. A wide range (eight orders of magnitude) is necessary to illustrate the normalized releases of radionuclides other than tritium in liquid effluents (Figure XVI); this may be a result of the radionuclides identified and of the hold-up times provided in the waste treatment systems. The distributions are similar, although that for GCRs is somewhat higher. A duality in the GCR distribution is again noted, this time taking the pattern for noble gases mentioned above (higher normalized releases from the older reactors).

141. The radionuclide composition of releases has been examined for the various reactor types. In general, the releases of noble gases from PWRs are dominated by ^{133}Xe, with a half-life of 5.3 days, but short-lived radionuclides such as ^{135}Xe (half-life = 9.2 h) are also present. For the BWRs the composition of the noble gas releases is more varied, with most krypton and xenon radionuclides included. The releases of particulates from BWRs are also variable and difficult to generalize from the limited data available. The radionuclides ^{88}Rb (half-life = 17.8 min), ^{89}Rb (half-life = 15.2 min), ^{138}Cs (half-life = 33.4 min), and ^{139}Ba (half-life = 83.1 min) were prominent in the large releases mentioned above from the Ringhals 1 reactor. The radionuclide compositions of liquid releases from PWRs seem to vary from reactor to reactor; the cobalt isotopes (^{58}Co, ^{60}Co) as well as the caesium isotopes (^{134}Cs, ^{137}Cs) are usually present. In some cases, large relative proportions of ^{110m}Ag and ^{124}Sb are reported. It may be that some differences are accentuated by the various measuring and reporting practices at reactor stations.

142. The longer-term temporal trends in normalized releases of radionuclides for the various reactor types are illustrated in Figure XVII. The trends are shown for the time designated "pre-1970" to 1994, averaged over five-year time periods, and for the three-year period from 1995 to 1997. Except for the atmospheric releases of particulates, the normalized releases are either fairly constant or slightly decreasing. The increased release of particulates to air reflects the operation of a specific reactor and is not characteristic of all reactors.

2. Local and regional dose estimates

143. The concentrations of the released radionuclides in the environment are generally too low to be measurable except close to the nuclear facility and then for a limited number of radionuclides only. Therefore, dose estimates for the population (individual and collective doses) are generally based on modelling the atmospheric and aquatic transport and environmental transfer of the released radioactive materials and then applying a dosimetric model.

144. The environmental and dosimetric models previously used for dose estimates were described in the UNSCEAR 1982 and 1988 Reports [U4, U6]. Based on the review in Annex A, "*Dose assessment methodologies*", the values of the dose coefficients for some radionuclides have been revised. The dose assessment procedures are applied to a model site with representative environmental conditions. The average population density is 20 km^{-2} within 2,000 km of the site. Within 50 km of the site, the population density is taken to be

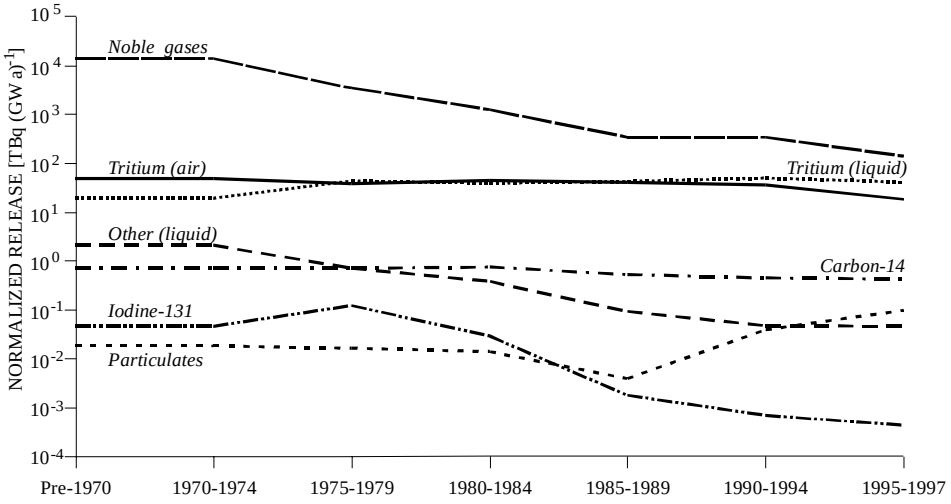


Figure XVII. Trends in releases of radionuclides from reactors.
Values of 1970–1974 are assumed to apply prior to 1970.

400 km^{-2}. For the model site the collective effective doses per unit release (man Sv PBq^{-1}) for the different release categories and reactor types are presented in Table 38. Because of the variability in annual releases, normalized releases [TBq (GW a)$^{-1}$] have been averaged over a five-year period (Table 37) to assess the collective dose.

145. The collective effective dose per unit electrical energy generated [man Sv (GW a)$^{-1}$] is obtained by multiplying the normalized releases per unit electrical energy generated (Table 37) by the collective effective dose per unit release (Table 38). The resulting estimates for 1990–1994 are given in Table 39. The total normalized collective effective dose for all reactors, weighted by the relative energy production of each reactor type (Table 39), is 0.43 man Sv (GW a)$^{-1}$. The radionuclide releases were generally similar to those that prevailed in the preceding five-year assessment period [U3], but revisions in the dose coefficients have reduced the normalized collective effective dose by a factor of 3.

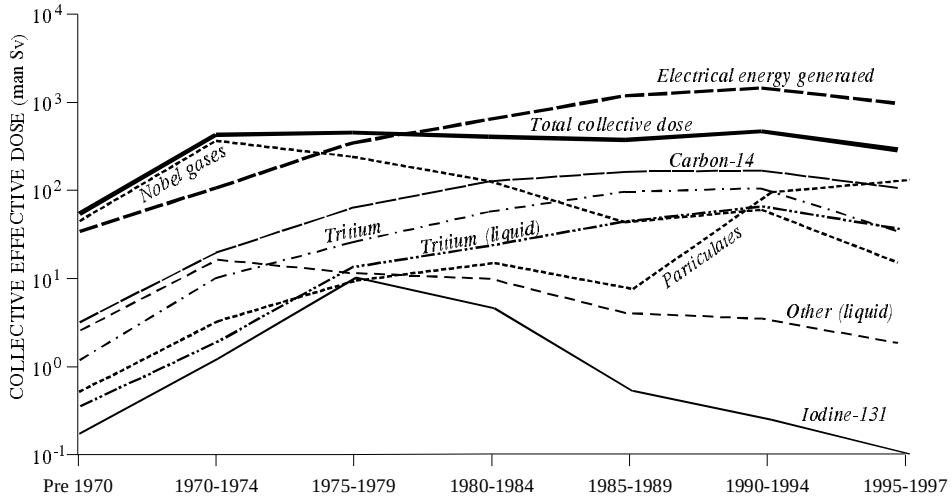


Figure XVIII. Local and regional collective effective doses from average annual releases of radionuclides from reactors. *The increasing trend in electrical energy generated is indicated with scale on left in units of GW a.*

146. From the total energy generated and the normalized collective dose, the local and regional collective dose from the operation of nuclear power plants during 1990–1994 is estimated to be 490 man Sv. During 1985–1989 the corresponding collective dose was 390 man Sv. This is an increase of just over 25%, which is nearly the same as the increase in the energy generated by nuclear reactors (1985–1989: 936 GW a; 1990–1994: 1,147 GW a). To reduce the effect of variability in annual releases, the calculation of the collective dose is based on normalized releases averaged over five-year periods (Table 37). However, outliers in the data set can still have a substantial impact on the dose estimate. If, for example, the particulate releases from the Ringhals 1 reactor are excluded, the corresponding dose estimates will be 0.39 man Sv (GW a)$^{-1}$ and 450 man Sv, respectively. However, this point could not be taken out of the data set without examining other possible outliers for 1990–1994 and for earlier years.

147. It should be noted that the average normalized doses derived here may not apply to specific reactors of a particular type. There may be further variations in release compositions,

population densities, and local environmental pathways that could significantly change the collective dose contributions. In a few cases, reactor operators report estimates of doses to local residents based on possible exposure scenarios. The data have, however, not been collected or assessed by the Committee.

148. The temporal trends of the local and regional collective effective doses for the different radionuclide categories over a longer time are shown in Figure XVIII. The collective dose from ^{131}I has decreased for a number of years, and this decrease continues for the latest five-year and three-year periods. The collective doses from tritium (airborne and liquid), ^{14}C, and particulates have been increasing through the 1990–1994 period. Overall, the total collective dose has been relatively constant since 1970–1979, even though the electrical energy generated has continuously increased.

149. For the model site, the annual average effective doses to individuals, estimated from the release data and assuming the total collective dose for a reactor type exposes a single local population group (400 km^{-2} to 50 km), are 5 μSv for PWRs and GCRs, 10 μSv for BWRs and HWRs, 2 μSv for LWGRs, and 0.04 μSv for FBRs. In comparison, reported annual individual doses from a number of reactor sites are in the range 1–500 μSv.

D. FUEL REPROCESSING

150. Fuel reprocessing is carried out to recover uranium and plutonium from spent fuel for reuse in reactors. Most spent fuel from reactors is retained on-site in interim storage, pending decisions on ultimate disposal or retrievable storage. Only about 5%–10% of fuel is submitted to the reprocessing stage of the nuclear fuel cycle. The main commercial reprocessing plants are in France, Japan, and the United Kingdom.

1. Effluents

151. Relatively large quantities of radioactive materials are involved at the fuel reprocessing stage. The radionuclides are freed from their contained state as the fuel is brought into solution, and the potential for release in waste discharges is greater than for other stages of the fuel cycle. Routine releases have been largely in liquid effluents to the sea. Operating standards have been considerably improved at these plants over the years, with substantial reductions occurring in released amounts.

152. Some revisions and additions have been made to the release quantities previously reported by the Committee. Also, more direct data on fuel throughput, which were previously estimated from ^{85}Kr discharges, are available. Therefore, the annual release data for fuel reprocessing plants from 1970 through 1997 are given in Table 40. The average normalized releases per unit of energy generated in five-year periods (except for 1970–1979, a 10-year period) are summarized in Table 41 and shown in Figure XIX. It can be observed that the releases to both air and sea of most radionuclides have been decreasing over the long term. This is particularly so for the releases of ^{106}Ru, ^{90}Sr, and ^{137}Cs to the sea and for ^{137}Cs and ^{131}I to the air (Table 41).

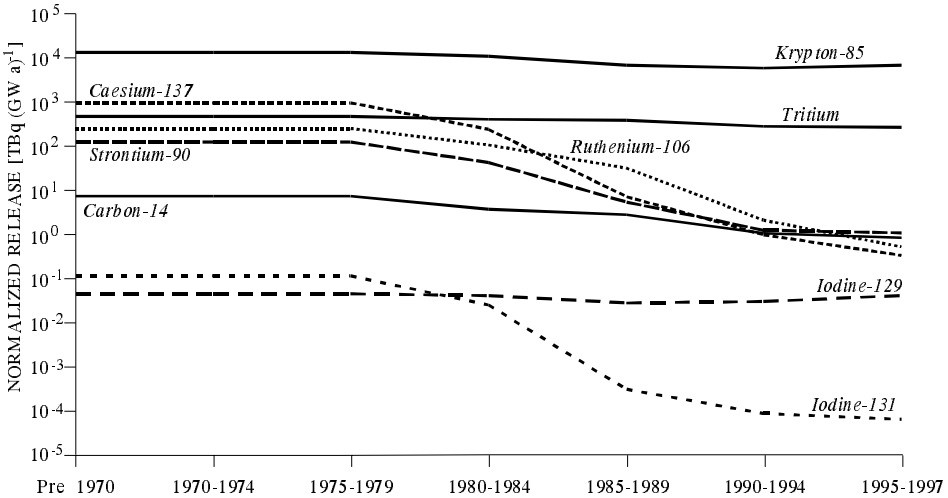


Figure XIX. Trends in releases of radionuclides from fuel reprocessing plants.
Average values ere derived for 1970-1979 and assumed to apply also prior to 1970.

2. Local and regional dose estimates

153. Collective doses from nuclear fuel reprocessing can be estimated from the normalized releases per unit of energy generated, the electrical energy equivalent of the fuel reprocessed, and the collective dose per unit release of radionuclides [U3]. This analysis is given in Table 41. For the entire period of fuel reprocessing, the total collective effective dose is estimated to be 4,700 man Sv. Liquid releases of ^{137}Cs contributed 87% of the total dose. The collective effective dose from each radionuclide is shown in Figure XX. In the most recent five-year period (1990–1994) the dose from ^{14}C exceeded that from ^{137}Cs. During the 1980s and 1990s, the collective dose from fuel reprocessing has been decreasing, even though the amount of fuel reprocessed has been increasing (Figure XX).

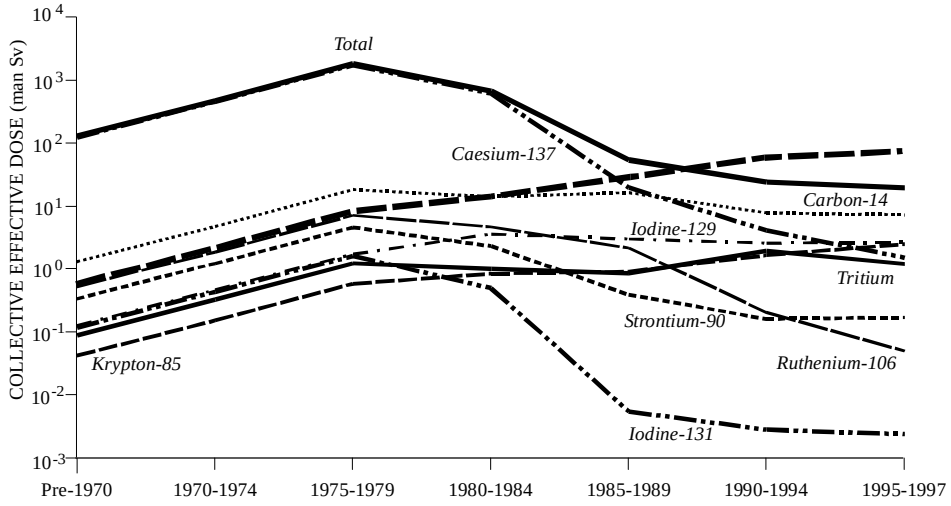


Figure XX. Local *and regional collective effective doses from average annual release of radionuclides from fuel reprocessing plants.* *The amount of fuel reprocessed is indicated by the heavy dashed line (units GW a).*

154. From the data provided in Table 41, it may be determined that the annual components of collective dose from fuel reprocessing are of the order of 20–30 man Sv. If this were received only by a single local population (3.1 10^6 persons within 50 km), the effective dose commitment to individuals would be about 10 µSv per year of operation. This dose commitment is delivered over a longer-term, especially from ^{14}C, and is distributed, as well, among separate installations (in three countries).

E. GLOBALLY DISPERSED RADIONUCLIDES

155. Radionuclides that are sufficiently long-lived and easily dispersed in the environment can give rise to global doses. The radionuclides of specific interest are ^{3}H, ^{14}C, ^{85}Kr, and ^{129}I, with half-lives of 12.26, 5,730, 10.7, and 1.6 10^7 years, respectively. The large uncertainties involved in estimating doses over prolonged time periods are due to problems in predicting environmental pathways, population distributions, dietary habits, climate change, etc. The uncertainties of dose calculations increase when the integration is carried out for very long periods of time, hundreds or thousands of years or even longer. In this assessment, as was done for the case of collective dose from mill tailings, the global dose commitments are truncated at 10,000 years.

156. The normalized releases of the globally dispersed radionuclides given in Tables 37 and 41 are summarized in Table 42. From the electrical energy generated or the energy equivalent of fuel reprocessed, the total activity release of these radionuclides may be calculated (Table 43). Applying the factors of collective dose per unit release to these results gives estimates of the collective effective dose commitments (Table 44). For the very long-lived radionuclides (^{14}C and ^{129}I), a world population of 10^{10} was assumed at the time of the release, and for ^{3}H and ^{85}Kr, a population of 5 10^9 was assumed.

157. The total collective effective dose per unit electrical energy generated is obtained from the normalized releases from reactors and reprocessing plants (Table 42) and the factors of collective dose per unit release (as revised in Annex A, "*Dose assessment methodologies*"). In normalizing to the total energy generated, the contribution from the reprocessing plants is weighted according to the fraction of the fuel reprocessed (0.11 for 1990–1994). The estimates of the normalized collective dose commitments are 41 and 43 man Sv $(GW\ a)^{-1}$ for 1990–1994 and 1995–1997, respectively, which are due mostly to ^{14}C (Table 44).

158. The commitment calculations may be used to indicate the maximum dose rate for a continuing practice. The ^{14}C collective dose commitment (10,000 years) based on present practice is roughly 40 man Sv $(GW\ a)^{-1}$. This means that a continuing practice of 250 GW a energy production each year into the future, as at present, would result in an maximum dose rate of 1 µSv a^{-1} [40 man Sv $(GW\ a)^{-1}$ × 250 GW a/a ÷ 10^{10} persons]. A limited practice of nuclear power generation would result in progressively less annual dose, e.g. a 100 or 200 year practice would cause 0.1 or 0.16 µSv a^{-1}, respectively (1950–2000 actual practice with 50 or 150 year projected releases as at present). This is illustrated in Figure XXI.

159. In a similar fashion, the maximum dose rates for the other globally dispersed radionuclides may be determined. These are of the order of 0.1 µSv a^{-1} for ^{85}Kr and 0.005 µSv a^{-1} for ^{3}H and ^{129}I. For limited duration practice, the maximum annual dose rates reached will be less. These are thus negligible annual dose rates for these globally dispersed radionuclides.

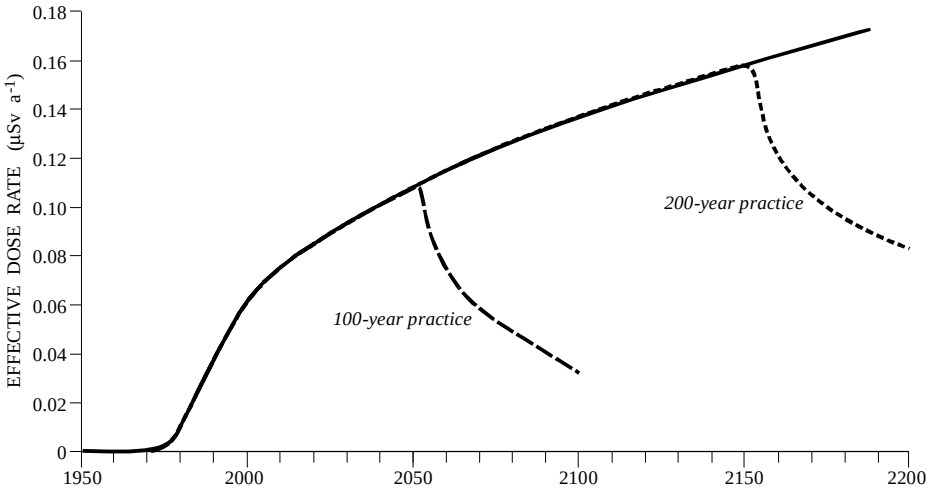


Figure XXI. Average annual dose rate from globally dispersed ^{14}C released from nuclear installations based on actual practice 1950–2000 and projection of current releases for the duration of the practice.
The equilibrium annual dose rate for a constant, continuing practice is 1 μSv a^{-1}.

F. SOLID WASTE DISPOSAL AND TRANSPORT

160. Solid wastes arise at various stages of the nuclear fuel cycle. They include low- and intermediate-level wastes, mainly from reactor operations, high-level wastes from fuel reprocessing, and spent fuel for direct disposal. Low- and intermediate-level wastes are generally disposed of by shallow burial in trenches or concrete-lined structures, but there are also more advanced disposal sites. High-level wastes and spent fuel are retained in interim storage tanks until adequate solutions for disposal have been devised and disposal sites have been selected.

161. Doses from solid waste disposal have been estimated based on the projected eventual migration of radionuclides through the burial site into groundwater. These estimates depend critically on the assumptions used for the containment of the solid wastes and the site characteristics and are, accordingly, highly uncertain in a general sense. The approximate normalized collective effective dose from low- and intermediate-level waste disposal is, however, quite low, of the order of 0.5 man Sv $(GW\ a)^{-1}$, due almost entirely to ^{14}C [U3, U4].

162. A repository for high-level waste and spent fuel has not yet been constructed. The radiological impact assessment of such a repository has to rely on modelling of the long-term behaviour of the waste packages and the migration of released radionuclides near the site and at greater distance over a long period of time. To carry out such performance assessments, a number of site-specific data, including waste characterization and transport models, are needed. Such assessments have been performed, mainly to help in formulating design criteria for the hypothetical repositories.

163. The transportation of radioactive materials of various types between nuclear fuel cycle installations may cause members of the public who happen to be near the transport vehicles to be exposed. Doses can be estimated only by applying hypothetical assumptions. A conservative estimate is, in this case, of the order of 0.1 man Sv $(GW\ a)^{-1}$ [U4].

164. Decommissioning of nuclear facilities gives rise to radioactive waste, and some experience is accumulating. The information available indicates that exposures of the public from the decommissioning practice will be very small.

G. SUMMARY OF DOSE ESTIMATES

165. The normalized collective effective doses to members of the public from radionuclides released in the various stages of the nuclear fuel cycle are summarized in Table 45. The local and regional collective dose in the two most recent assessment periods is 0.9 man Sv $(GW\ a)^{-1}$. The largest part of this dose is received within a limited number of years after the releases and is mainly due to the normal operation of nuclear reactors and mining operations. The global dose, which is estimated for 10,000 years, amounts to 50 man Sv $(GW\ a)^{-1}$. The main contribution is from globally dispersed ^{14}C (reactors and reprocessing). The longer-term trends in collective effective doses per unit electrical energy generated show decreases, attributable to reductions in the release of radionuclides from reactors and fuel reprocessing plants. The components of normalized collective effective dose have decreased by much more than an order of magnitude for releases from reprocessing plants, by a factor of 7 for releases from reactors, and by a factor of 2 for globally dispersed radionuclides, compared to the earliest assessment period, 1970–1979.

166. The local and regional collective dose from the beginning of nuclear power production can be derived from the normalized collective doses (Table 45) and the electrical energy generated in each period (Table 43). The result is about 5,000 man Sv from fuel reprocessing, 3,000 man Sv from reactor operations, and 900 man Sv from mining and

milling. This analysis is summarized in Table 46. In recent years, the annual total from all these operations amounts to 200 man Sv received by the local and regional population. Assuming that the current practice of nuclear power production continues for 100 years, the maximum per caput dose can be estimated from the truncated collective dose per unit electrical energy generated. Figure XXI shows that about 10% of the dose from globally dispersed radionuclides is committed in the first hundred years, and using Table 45, the collective effective dose in the hundredth year of the practice, from globally dispersed radionuclides, would be 5 man Sv $(GW\ a)^{-1}$. For an annual production of 250 GW a this amounts to 1,250 man Sv per year, which when added to the local and regional dose of 200 man Sv per year gives a total dose of nearly 1,500 man Sv in the last year of the practice. The maximum annual effective dose arising from 100 years of the practice of nuclear power production is then less than 0.2 μSv per caput for a global population of 10^{10} persons.

III. OTHER EXPOSURES

A. RADIOISOTOPE PRODUCTION AND USE

167. Radioisotopes are widely used in industry, medicine, and research. Exposures may occur from trace amounts released in production or at subsequent stages of the use or disposal of the radionuclide-containing products. For very long-lived radionuclides such as ^{14}C, all of the amount utilized may ultimately reach the environment. For short-lived radionuclides such as most radiopharmaceuticals, radioactive decay prior to release is an essential consideration. The isotopes used most widely in medical examinations and nuclear medicine procedures are ^{131}I and ^{99m}Tc.

168. Estimates of doses from radioisotope production and use are uncertain, owing to limited data on the commercial production of the radioisotopes and on the release fractions from production and use. The main radionuclides of interest are ^{3}H, ^{14}C, ^{125}I, ^{131}I, and ^{133}Xe. The estimated annual collective effective dose from the practice is of the order of 100 man Sv [U3].

169. An important use of radionuclides is in medical diagnostic examinations and in therapeutic treatments. Medical radioisotopes or their parent radionuclides can be produced in a reactor (by fission of uranium, e.g. ^{99}Mo, ^{131}I, or by activation, e.g. ^{59}Fe) or in a cyclotron (by nuclear reaction, e.g.^{123}I, ^{201}Tl). The main radioisotope, used in 80% of all diagnostic examinations, is ^{99}Mo. In many countries the production, isolation, and incorporation of the radioisotopes into generators, diagnostic kits, or pharmaceuticals are often subdivided in different facilities [K11]. As an example, several research reactors in neighbouring countries supply ^{99}Mo to the radioisotope production plant in Belgium [W6]. Three different facilities are involved in the Netherlands in the generation of ^{99}Mo, its extraction and incorporation into ^{99m}Tc generators [L10]. This subdivision of the manufacturing process hampers quantification of the fractional release amounts from the overall production phase.

170. In its request for a permit in 1996, a medical radioisotope production plant in the Netherlands reported a controlled annual release of ^{131}I to the atmosphere of at most 300 MBq. Since it handles more than 52 TBq in a year, the release fraction would be less than 0.001%. The maximum annual dose to an individual from this release would 1 μSv [L10]. This plant receives the ^{131}I as raw material delivered from another company. Therefore, the data are unsuited for the entire production phase.

171. Over the period 1989–1992, a single facility supplied 90% of the annual amount of ^{131}I (35.9 TBq) used in China and 100% of the ^{125}I (0.98 TBq) [P7]. The average release fraction was reported to be 0.01% for ^{131}I (a reduction from 4.6% in 1975–1978) and 0.7% for ^{125}I. The annual collective dose was estimated to be 0.13 man Sv for ^{131}I and 0.1–0.6 man Sv for ^{125}I, assuming a local population density of 500 km^{-2}. The collective dose per unit release of ^{131}I is thus 36 man Sv TBq^{-1}. This may be compared with 0.3 man Sv TBq^{-1} that was estimated for release from a representative nuclear installation (Table 38).

172. Global usage of ^{131}I in nuclear therapy is approximately 600 TBq (Table 47). With application of the above dose factors, and assuming the release fraction on production to be 0.01%, the global annual collective dose from ^{131}I production and usage is 0.02–2 man Sv. A further contribution to the collective dose arises from wastes discharged from hospitals.

173. Limited data on ^{131}I releases from hospitals were cited in the UNSCEAR 1993 Report [U3]. Discharges of ^{131}I from hospitals in Australia and Sweden in the late 1980s corresponded to 110–190 GBq per 10^6 population [U3]. There is high excretion of ^{131}I from patients following oral administration, but waste treatment systems with hold-up tanks are effective in reducing the amounts in liquid effluents to $5\ 10^{-4}$ of the amounts administered to patients [J4]. This seems to be confirmed by the very low concentrations of ^{131}I measured in the surface waters and sewage systems of several countries [U3]. This information seems not to be systematically collected.

174. With the estimated global annual usage of ^{131}I in therapeutic treatments of 600 TBq, a release fraction of $5\ 10^{-4}$ and a dose coefficient of 0.03 man Sv TBq^{-1} for ^{131}I released in liquid effluents (from Annex A, "*Dose assessment methodologies*"), the further contribution to the collective dose is just 0.009 man Sv. The presence of the hold-up tanks should reduce the release of ^{99m}Tc, the other major radionuclide, to negligible levels.

175. Several recent studies consider the external exposure of the groups that are mainly exposed, i.e. parents, infants, who come in contact with therapeutically treated patients or fellow travellers on the journey home from the hospital [B12, C12, D8, G9, M11]. These assessments are based either on use of integrating dosimeters or on dose-rate measurements close to the patients with appropriate occupancy factors. Assessments based on the first approach gave doses of 0.04–7 mSv to partners and children of the patients treated for hyperthyroidism with 200–800 MBq of ^{131}I [B12, M11]. Average doses were 1 mSv to partners and 0.1 mSv to children [M11]. Treatment of thyroid cancer patients with 4–7 GBq of ^{131}I resulted in doses below 0.5 mSv to family members [M11]. All of about 200 family members involved in these studies were given advice, according to current practice, about limiting close contact with the patient. Dose rates to fellow travellers ranged from 0.02–0.5 mSv h^{-1}.

176. An approximate estimate of the collective dose to family members of patients therapeutically treated with ^{131}I can be derived as follows. In developed countries about 20% of therapeutic treatments with ^{131}I are for thyroid cancer and 80% for hyperthyroidism with average administered amounts of 5 GBq and 0.5 GBq, respectively. The weighted average amount administered is thus 1.4 GBq per patient. For global usage of 600 TBq of ^{131}I, 430,000 patients could be treated. With average exposures of 0.5 mSv to 2–3 family members, the collective dose to those other than the patients could be 400–600 man Sv.

177. The importance of inhalation of radioiodine exhaled by patients treated with radioiodine (0.3–1.3 GBq), was assessed by whole body measurements of their relatives [W7]. The effective dose ranged from 0.3 to about 60 μSv (17 persons) with a median value of about 4 μSv. Diagnostic procedures with most radionuclides are estimated to result in cumulative doses of less than 40 μSv to someone who remains in the close vicinity of the patient [B13]. Breast feeding following maternal radiopharmaceutical administration may result in an effective dose to the infant of more than 1 mSv, if the feeding is not temporarily interrupted or ceased. This is the case for a limited number of treatments with radioiodine but also for some with ^{99m}Tc and ^{67}Ga [M11, M12].

178. The most important component in the overall dose to the general population from radioisotope production and usage is that to relatives of patients given therapeutic treatments. The dominant component of the global collective dose is from ^{131}I. It was assumed that decay between production and use of the isotope can be neglected, which means that the data on isotope consumption can be used. The resulting global annual collective dose is estimated to range up to about 600 man Sv. The small doses to relatives of patients after diagnostic procedures may add up to a comparable collective dose, since their number exceeds that of the therapeutic treatments by two orders of magnitude. The dose to family members was not considered in the previous assessment by the Committee in the UNSCEAR 1993 Report [U3]. The earlier estimate of 100 man Sv, of which 80% was from ^{14}C, represented possible releases mainly at the production stage. Since this estimate is quite uncertain and likely an overestimate, it is seen that the exposure of family members of patients treated with ^{131}I may be considered to be the most important component of exposure to radioisotopes used in medicine, industry and education.

B. RESEARCH REACTORS

179. Research reactors differ from reactors producing electrical energy in their wide variety of designs and modes of operation, as well as a wide range of use. Research reactors are used for tests of nuclear fuels and different materials, for investigations in nuclear and neutron physics, biology, and medicine, and for the production of radioisotopes. At the end of 1999, there were 292 nuclear research reactors operating in the world, with a total thermal energy of 3,000 MW. The total operating experience exceeds 13,000 reactor-years. The Committee has not previously collected data on releases of radionuclides from research reactors.

180. Exposures resulting from the operation of research reactors are exemplified by some data reported from the Russian Federation. From 1993 to 1996, annual releases from two research reactors in Obninsk averaged 0.7 PBq of noble gases, 5 GBq ^{131}I, 0.3 GBq ^{90}Sr, 0.6 GBq ^{137}Cs, and 0.1 GBq plutonium [M8, M10]. The annual effective doses to individuals in Obninsk were estimated not to exceed 30 μSv [M8]. Further data on research reactors are not available.

C. ACCIDENTS

181. Accidents involving releases of radionuclides to the environment occur from time to time. To the extent that these result in significant human exposures, they are reviewed and analysed. A separate Chapter on accidents was included in the UNSCEAR 1993 Report [U3], and a brief account was given of all earlier accidents. Since then only one accident has occurred at a nuclear installation involving some exposure of the local population. This was the accident on 30 September 1999 at the Tokaimura nuclear fuel processing plant in Japan [J6]. A criticality event took place because of improper procedures. During the 24-hour event and because of only limited shielding provided by the building, some direct irradiation was measurable outside the plant site. There was only trace release of gaseous fission products. Three workers inside the plant received serious overexposures. Their doses were estimated to be in the range 16–20 Gy, 6–10 Gy, and 1–4.5 Gy (gamma equivalent dose). The doses to 169 other employees were determined from personal dosimeters, whole-body counting, and survey of their locations during the accident [I8, J6, S9]. Doses to members of the public, about 200 in all, who were living or working within 350 m of the facility were estimated individually [F6]. Direct exposures to persons outside the site were estimated to be up to 21 mGy (gamma plus neutron). The highest dose, estimated by whole-body counting, was received by a person at a construction company just beyond the plant boundary.

182. The misuse or mishandling of radiation sources is generally a hazard to workers. Improper administration of thera-

peutic treatment sometimes result in accidental overexposures of patients. Lost or unregulated (orphaned) sources can cause exposures of the public. These topics are considered further in the separate assessments by the Committee of occupational and medical radiation exposures. The Committee has no other information on recent accidents that may have involved exposures of the public. The Committee has begun a more complete analysis of the doses and effects from the Chernobyl accident in the populations living nearest to the reactor in areas of the former Soviet Union. These results are presented separately in Annex J, "*Exposures and effects of the Chernobyl accident*".

CONCLUSIONS

183. Releases of radioactive materials to the environment and exposures of human populations have occurred in several activities, practices, and events involving radiation sources. The main contribution to the collective doses to the world population in such cases has come from the testing of nuclear weapons in the atmosphere. This practice occurred from 1945 through 1980. Each nuclear test resulted in unrestrained release to the environment of substantial quantities of radioactive materials. These were widely dispersed in the atmosphere and deposited everywhere on the earth's surface.

184. The Committee has given special attention to the evaluation of exposures from atmospheric nuclear testing. Numerous measurements of the global deposition of ^{90}Sr and ^{137}Cs and of the occurrence of these and other fallout radionuclides in diet and the human body were made at the time the testing was taking place. The worldwide collective dose from this practice was evaluated in the UNSCEAR 1982 Report [U6], and a systematic listing of transfer coefficients for a number of fallout radionuclides was given in the UNSCEAR 1993 Report [U3].

185. New information has become available on the numbers and yields of nuclear tests. These data were not fully revealed earlier by the countries that conducted the tests because of military sensitivities. An updated listing of atmospheric nuclear tests conducted at each of the test sites is included in this Annex. Although the total explosive yields of each test have been divulged, the fission and fusion yields are still mostly suppressed. Some general assumptions have been made to allow specifying the fission and fusion yields of each test in order to estimate the amounts of radionuclides produced in the explosions. The estimated total of fission yields of individual tests is in agreement with the global deposition of the main fission radionuclides ^{90}Sr and ^{137}Cs, as determined by worldwide monitoring networks.

186. With improved estimates of the production of each radionuclide in individual tests and using an empirical atmospheric transport model, it is possible to determine the time course of the dispersion and deposition of radionuclides and to estimate the annual doses from various pathways in each hemisphere of the world. In this way it has been estimated that the world average annual effective dose reached a peak of 110 μSv in 1963 and has since decreased to about 5 μSv, from residual levels in the environment, mainly of ^{14}C, ^{90}Sr, and ^{137}Cs. The average annual doses are 10% higher than the world average in the northern hemisphere, where most of the testing took place, and much lower in the southern hemisphere. Although there was considerable concern at the time of testing, the exposures remained relatively low, reaching at most about 5% of the background level from natural radiation sources.

187. The exposures to local populations surrounding the test sites have also been assessed using available information. The level of detail is still not sufficient to document the exposures with great accuracy. Attention to the local conditions and the possibilities of exposure was not great in the early years of the test programmes. However, dose reconstruction efforts are proceeding to clarify this experience and to document the local and regional exposures that occurred.

188. Underground testing caused exposures beyond the test sites only if radioactive gases leaked or were vented. Most underground tests had a much lower yield than atmospheric tests, and it was usually possible to contain the debris. Underground tests were conducted at the rate of 50 or more per year from 1962 to 1990. Although it is the intention of most countries to agree to ban all further tests, both atmospheric and underground, the treaty has not yet come into force. Further underground testing occurred in 1998. Thus, it cannot yet be stated that the practice has ceased.

189. During the time when nuclear weapons arsenals were being built up and especially in the earlier years (1945–1960), there were releases of radionuclides and exposures of local populations downwind or downstream of nuclear installations. Since there was little recognition of exposure potentials and monitoring of releases was limited, the exposure evaluations must be based on the reconstruction of doses. Results are still being obtained that document this experience. Practices have greatly improved and arsenals are now being reduced.

190. A continuing practice is the generation of electrical energy by nuclear power reactors. In recent years, 17% of the world's electrical energy has been generated by this means. During routine operation of nuclear installations, the releases of radionuclides are low, and exposures must be estimated with environmental transfer models. For all fuel cycle operations (mining and milling, reactor operation, and fuel reprocessing) the local and regional exposures are estimated

at present to be 0.9 man Sv $(GW\ a)^{-1}$. With present world nuclear energy generation of 250 GW a, the collective dose per year of practice is of the order of 200 man Sv. The assumed representative local and regional population surrounding a single installation is about 250 million persons, and the per caput dose to this population would be less than 1 μSv. The collective doses from globally dispersed radionuclides are delivered over very long periods and to the projected maximum population of the world. If the practice of nuclear power production is limited to the next 100 years at the present capacity, the maximum annual effective dose per caput to the global population would be less than 0.2 μSv. This dose rate is small compared to that from natural background radiation.

191. Except in the case of accidents, in which more localized areas can be contaminated to significant levels, there are no other practices that result in important exposures from radionuclides released to the environment. Estimates of releases of isotopes produced and used in industrial and medical applications are being reviewed, but these seem to be associated with rather insignificant levels of exposure. The highest exposures, averaging about 0.5 mSv, may be received by family members of patients who have received ^{131}I therapeutic treatments. Possible future practices, such as weapons dismantling, decommissioning of installations, and waste management projects, can be reviewed as experience is acquired, but these should all involve little or no release of radionuclides and consequently little or no exposure.

Table 1
Atmospheric nuclear tests

CHINA

Date	*Type of test*	*Yield (Mt)* [a]			*Partitioned fission yield (Mt)*		
		Fission	*Fusion*	*Total*	*Local and regional*	*Troposphere*	*Stratosphere*
Test site: Lop Nor							
1964: 16 October	Land surface	0.02	0	0.02	0.01	0.01	
1965: 14 May	Air	0.04	0	0.04		0.037	0.003
1966: 9 May 27 October 28 December	Air Air Land surface	0.2 0.02 0.2	0.1 0 0.1	0.3 0.02 0.3	 0.10	0.11 0.02 0.056	0.09 0.044
1967: 17 June 24 December	Air Air	1.7 0.02	1.3 0	3 0.02		 0.02	1.7
1968: 28 December	Air	1.5	1.5	3			1.5
1969: 29 September	Air	1.9	1.1	3			1.9
1970: 14 October	Air	1.9	1.1	3			1.9
1971: 18 November	Land surface	0.02	0	0.02	0.01	0.01	
1972: 7 January 18 March	Air Air	0.02 0.1	0 0	0.02 0.1		0.02 0.08	 0.02
1973: 27 June	Air	1.4	1.1	2.5			1.4
1974: 17 June	Air	0.3	0.3	0.6		0.065	0.235
1976: 23 January 26 September 17 November	Land surface Air Air	0.02 0.1 2.2	0 0 1.8	0.02 0.1 4	0.01 	0.01 0.08 	 0.02 2.2
1977: 17 September	Air	0.02	0	0.02		0.02	
1978: 15 March 14 December	Land surface Land surface	0.02 0.02	0 0	0.02 0.02	0.01 0.01	0.01 0.01	
1980: 16 October	Air	0.5	0.1	0.6		0.11	0.39

FRANCE

Date	*Type of test*	*Yield (Mt)* [a]			*Partitioned fission yield (Mt)*		
		Fission	*Fusion*	*Total*	*Local and regional*	*Troposphere*	*Stratosphere*
Test site: Algeria							
1960: 13 February 1 April 27 December	Tower Land surface Tower	0.067 [b] 0.003 [b] 0.002 [b]	0 0 0	0.067 0.003 0.002	0.0335 0.0015 0.001	0.0326 0.0015 0.001	0.0009
1961: 25 April	Tower	0.0007 [b]	0	0.0007	0.00035	0.00035	
Test site: Fangataufa							
1966: 24 September	Barge	0.125 [b]	0	0.125	0.0625	0.0595	0.003
1968: 24 August	Balloon	1.3	1.3	2.6			1.3
1970: 30 May 3 August	Balloon Balloon	0.4725 0.072	0.4725 0	0.945 0.072		 0.07	0.4725 0.002

Table 1 (continued)

Date	*Type of test*	*Yield (Mt)* [a]			*Partitioned fission yield (Mt)*		
		Fission	*Fusion*	*Total*	*Local and regional*	*Troposphere*	*Stratosphere*
Test site: Mururoa							
1966: 2 July	Barge	0.028 [b]	0	0.028	0.014	0.014	
19 July	Air drop	0.05 [b]	0	0.05		0.049	0.001
11 September	Balloon	0.11 [b]	0	0.11			0.11
4 October	Barge	0.205 [b]	0	0.205	0.1025	0.0921	0.0104
1967: 5 June	Balloon	0.015 [b]	0	0.015		0.015	
27 June	Balloon	0.12 [b]	0	0.12			0.12
2 July	Barge	0.022 [b]	0	0.022	0.011	0.011	
1968: 7 July	Balloon	0.115 [b]	0	0.115			0.115
15 July	Balloon	0.45 [b]	0	0.45			0.45
3 August	Balloon	0.15 [b]	0	0.15			0.15
8 September	Balloon	0.64	0.64	1.28			0.64
1970: 15 May	Balloon	0.013 [b]	0	0.013		0.013	
22 May	Balloon	0.150	0.074	0.224			0.150
24 June	Balloon	0.012 [b]	0	0.012		0.012	
3 July	Balloon	0.457	0.457	0.914			0.457
27 July	Balloon	0.00005 [b]	0	0.00005		0.00005	
6 August	Balloon	0.297	0.297	0.594			0.297
1971: 5 June	Balloon	0.034 [b]	0	0.034		0.034	
12 June	Balloon	0.29	0.15	0.44			0.29
4 July	Balloon	0.009 [b]	0	0.009		0.009	
8 August	Balloon	0.004 [b]	0	0.004		0.004	
14 August	Balloon	0.478	0.477	0.955			0.478
1972: 25 June	Balloon	0.0005 [b]	0	0.0005		0.0005	
30 June	Balloon	0.004 [b]	0	0.004		0.004	
27 July	Balloon	0.006 [b]	0	0.006		0.006	
1973: 21 July	Balloon	0.011 [b]	0	0.011		0.011	
28 July	Balloon	0.00005 [b]	0	0.00005		0.00005	
18 August	Balloon	0.004 [b]	0	0.004		0.004	
24 August	Balloon	0.0002 [b]	0	0.0002		0.0002	
28 August	Air drop	0.006 [b]	0	0.006		0.006	
1974: 16 June	Balloon	0.004 [b]	0	0.004		0.004	
7 July	Balloon	0.10	0.05	0.15			0.10
17 July	Balloon	0.004 [b]	0	0.004		0.004	
25 July	Air drop	0.008 [b]	0	0.008		0.008	
15 August	Balloon	0.096	0	0.096		0.093	0.003
24 August	Balloon	0.014 [b]	0	0.014		0.014	
14 September	Balloon	0.221	0.111	0.332			0.221

UNITED KINGDOM

Date	*Type of test*	*Yield (Mt)* [a]			*Partitioned fission yield (Mt)*		
		Fission	*Fusion*	*Total*	*Local and regional*	*Troposphere*	*Stratosphere*
Test site: Monte Bello Islands, Australia							
1952: 3 October	Water surface	0.025	0	0.025	0.0125	0.0125	
1956: 16 May	Tower (31 m)	0.015	0	0.015	0.0075	0.0075	
19 June	Tower (31 m)	0.06	0	0.06	0.03	0.0293	0.0007
Test site: Emu, Australia							
1953: 14 October	Tower (31 m)	0.01	0	0.01	0.005	0.005	
26 October	Tower (31 m)	0.008	0	0.008	0.004	0.004	

Table 1 (continued)

Date	*Type of test*	*Yield (Mt)* [a]			*Partitioned fission yield (Mt)*		
		Fission	*Fusion*	*Total*	*Local and regional*	*Troposphere*	*Stratosphere*
Test site: Maralinga, Australia							
1956: 27 September	Tower (31 m)	0.015	0	0.015	0.0075	0.0075	
4 October	Land surface	0.0015	0	0.0015	0.00075	0.00075	
11 October	Air drop (150 m)	0.003	0	0.003		0.003	
22 October	Tower (31 m)	0.01	0	0.01	0.005	0.005	
1957: 14 September	Tower (31 m)	0.001	0	0.001	0.0005	0.0005	
25 September	Tower (31 m)	0.006	0	0.006	0.003	0.003	
9 October	Balloon (300 m)	0.025	0	0.025		0.025	
Test site: Malden Island, Pacific							
1957: 15 May	Air burst	0.2	0.1	0.3		0.17	0.03
31 May	Air burst	0.36	0.36	0.72		0.265	0.095
19 June	Air burst	0.13	0.07	0.20		0.12	0.01
Test site: Christmas Island, Pacific							
1957: 8 November	Air burst	0.9	0.9	1.8		0.315	0.585
1958: 28 April	Air burst	1.5	1.5	3		0.12	1.38
22 August	Air burst	0.024	0	0.024		0.024	
2 September	Air burst	0.5	0.5	1		0.325	0.175
11 September	Air burst	0.4	0.4	0.8		0.285	0.115
23 September	Air burst	0.025	0	0.025		0.025	

UNITED STATES

Date	*Type of test*	*Yield (Mt)* [a]			*Partitioned fission yield (Mt)*		
		Fission	*Fusion*	*Total*	*Local and regional*	*Troposphere*	*Stratosphere*
Test site: New Mexico							
1945: 16 July	Tower	0.021	0	0.021	0.011	0.01	
Hiroshima and Nagasaki, Japan (combat use)							
1945: 5 August	Air drop	0.015	0	0.015		0.015	
9 August	Air drop	0.021	0	0.021		0.021	
Test site: Nevada							
1951: 27 January	Air drop (320 m)	0.001	0	0.001		0.001	
28 January	Air drop (330 m)	0.008	0	0.008		0.008	
1 February	Air drop (330 m)	0.001	0	0.001		0.001	
2 February	Air drop (335 m)	0.008	0	0.008		0.008	
6 February	Air drop (340 m)	0.022	0	0.022		0.022	
22 October	Tower (100 m)	0.0001	0	0.0001	0.00005	0.00005	
28 October	Air drop (340 m)	0.0035	0	0.0035		0.0035	
30 October	Air drop (340 m)	0.014	0	0.014		0.014	
1 November	Air drop (430 m)	0.021	0	0.021		0.021	
5 November	Air drop (900 m)	0.031	0	0.031		0.031	
19 November	Surface	0.012	0	0.0012	0.0006	0.0006	
29 November	Surface (-5 m)	0.001	0	0.001	0.0005	0.0005	
1952: 1 April	Air drop (240 m)	0.001	0	0.001		0.001	
15 April	Air drop (320 m)	0.001	0	0.001		0.001	
22 April	Air drop (1050 m)	0.031	0	0.031		0.031	
1 May	Air drop (300 m)	0.019	0	0.019		0.019	
1952: 7 May	Tower (90 m)	0.012	0	0.012	0.006	0.006	
25 May	Tower (90 m)	0.011	0	0.011	0.0055	0.0055	
1 June	Tower (90 m)	0.015	0	0.015	0.0075	0.0075	
5 June	Tower (90 m)	0.014	0	0.014	0.007	0.007	

Table 1 (continued)

Date	*Type of test*	*Yield (Mt)* [a]			*Partitioned fission yield (Mt)*		
		Fission	*Fusion*	*Total*	*Local and regional*	*Troposphere*	*Stratosphere*
Test site: Nevada (continued)							
1953: 17 March	Tower (90 m)	0.016	0	0.016	0.008	0.008	
24 March	Tower (90 m)	0.024	0	0.024	0.012	0.012	
31 March	Tower (90 m)	0.0002	0	0.0002	0.0001	0.0001	
6 April	Air drop (1835 m)	0.011	0	0.011		0.011	
11 April	Tower (30 m)	0.0002	0	0.0002	0.0001	0.0001	
18 April	Tower (90 m)	0.023	0	0.023	0.012	0.011	
25 April	Tower (90 m)	0.043	0	0.043	0.022	0.021	
8 May	Air drop (740 m)	0.027	0	0.027		0.027	
19 May	Tower (90 m)	0.032	0	0.032	0.016	0.016	
25 May	Airburst (160 m)	0.015	0	0.015		0.015	
4 June	Air drop (400 m)	0.061	0	0.061		0.0595	0.0015
1955: 18 February	Air drop (230 m)	0.001	0	0.001		0.001	
22 February	Tower (90 m)	0.002	0	0.002	0.001	0.001	
1 March	Tower (90 m)	0.007	0	0.007	0.0035	0.0035	
7 March	Tower (150 m)	0.043	0	0.043	0.0215	0.0215	
12 March	Tower (90 m)	0.004	0	0.004	0.002	0.002	
22 March	Tower (150 m)	0.008	0	0.008	0.004	0.004	
29 March	Tower (150 m)	0.014	0	0.014	0.007	0.007	
29 March	Air drop (225 m)	0.003	0	0.003		0.003	
6 April	Air drop (1120 m)	0.003	0	0.003		0.003	
9 April	Tower (90 m)	0.002	0	0.002	0.001	0.001	
15 April	Tower (120 m)	0.022	0	0.022	0.011	0.011	
5 May	Tower (150 m)	0.029	0	0.029	0.0145	0.0145	
15 May	Tower (1560 m)	0.028	0	0.028	0.014	0.014	
1957: 28 May	Tower (150 m)	0.012	0	0.012	0.006	0.006	
2 June	Tower (90 m)	0.00014	0	0.00014	0.00007	0.00007	
5 June	Balloon (150 m)	0.0000005	0	0.0000005		0.0000005	
18 June	Balloon (150 m)	0.01	0	0.01		0.01	
24 June	Balloon (210 m)	0.037	0	0.037		0.037	
5 July	Balloon (460 m)	0.074	0	0.074		0.072	0.002
15 July	Tower (150 m)	0.017	0	0.017	0.0085	0.0085	
19 July	Rocket (6100 m)	0.002	0	0.002		0.002	
24 July	Tower (150 m)	0.01	0	0.01	0.005	0.005	
25 July	Balloon (150 m)	0.0097	0	0.0097		0.0097	
7 August	Balloon (460 m)	0.019	0	0.019		0.019	
18 August	Tower (150 m)	0.017	0	0.017	0.0085	0.0085	
23 August	Balloon (460 m)	0.011	0	0.011		0.011	
30 August	Balloon (230 m)	0.0047	0	0.0047		0.0047	
31 August	Tower (210 m)	0.044	0	0.044	0.022	0.022	
2 September	Tower (150 m)	0.011	0	0.011	0.0055	0.0055	
6 September	Balloon (150 m)	0.0002	0	0.0002		0.0002	
8 September	Balloon (230 m)	0.001	0	0.001		0.001	
14 September	Tower (150 m)	0.011	0	0.011	0.0055	0.0055	
16 September	Balloon (460 m)	0.012	0	0.012		0.012	
23 September	Tower (150 m)	0.019	0	0.019	0.0095	0.0095	
28 September	Balloon (460 m)	0.012	0	0.012		0.012	
7 October	Balloon (460 m)	0.008	0	0.008		0.008	
1958: 19 September	Balloon (150 m)	0.000083	0	0.000083		0.000083	
29 September	Balloon (460 m)	0.002	0	0.002		0.002	
10 October	Tower (30 m)	0.000079	0	0.000079	0.00004	0.000039	
13 October	Balloon (460 m)	0.0014	0	0.0014		0.0014	
15 October	Tower (15 m)	0.0000012	0	0.0000012	0.0000006	0.0000006	
16 October	Balloon (140 m)	0.000037	0	0.000037		0.000037	
18 October	Tower (22 m)	0.00009	0	0.00009	0.000045	0.000045	
22 October	Balloon (440 m)	0.006	0	0.006		0.006	
22 October	Balloon (460 m)	0.00012	0	0.00012		0.00012	
22 October	Balloon (150 m)	0.00019	0	0.00019		0.00019	
26 October	Balloon (460 m)	0.0049	0	0.0049		0.0049	
26 October	Balloon (460 m)	0.0022	0	0.0022		0.0022	
29 October	Tower (10 m)	0.0000078	0	0.0000078	0.0000039	0.0000039	
29 October	Tower	0	0	0	0	0	
30 October	Balloon(460 m)	0.0013	0	0.0013		0.0013	
1962: 11 July	Surface (- 1 m)	0.0005	0	0.0005	0.00025	0.00025	
7 July	Surface	0.02	0	0.02 [c]	0.01	0.01	
14 July	Tower	0.02	0	0.02 [c]	0.01	0.01	
17 July	Surface	0.02	0	0.02 [c]	0.01	0.01	

Table 1 (continued)

Date	*Type of test*	*Yield (Mt)* [a]			*Partitioned fission yield (Mt)*		
		Fission	*Fusion*	*Total*	*Local and regional*	*Troposphere*	*Stratosphere*
Test site: Bikini, Pacific							
1946: 30 June	Air drop	0.021	0	0.021		0.021	
24 July	Underwater (-30 m)	0.021	0	0.021	0.011	0.01	
1954: 28 February	Surface	9 [d]	6	15	4.5		4.5
26 March	Barge	7.3 [d]	3.7	11	3.65		3.65
6 April	Surface	0.075	0.035	0.11	0.037	0.037	0.001
25 April	Barge	4.6 [d]	2.3	6.9	2.3		2.3
4 May	Barge	9.0 [d]	4.5	13.5	4.5		4.5
1956: 20 May	Air drop	1.6 [d]	2.2	3.8		0.076	1.52
27 May	Surface	1.25 [d]	2.25	3.5	0.625	0.038	0.587
11 June	Barge	0.183 [d]	0.182	0.365	0.092	0.077	0.014
25 June	Barge	0.55	0.55	1.1	0.275	0.168	0.107
10 July	Barge	1.5 [d]	3.0	4.5	0.75	0.018	0.732
20 July	Barge	2.3 [d]	2.7	5	1.15	0.005	1.145
1958: 11 May	Barge	0.68	0.68	1.36	0.34	0.175	0.165
21 May	Barge	0.0251	0	0.0251	0.0126	0.0125	
31 May	Barge	0.092	0	0.092	0.046	0.0446	0.0014
10 June	Barge	0.142	0.071	0.213	0.071	0.063	0.008
14 June	Barge	0.212	0.107	0.319	0.106	0.091	0.015
27 June	Barge	0.275	0.137	0.412	0.137	0.164	0.024
29 June	Barge	0.014	0	0.014	0.007	0.007	
2 July	Barge	0.15	0.07	0.22	0.075	0.076	
12 July	Barge	3.2 [d]	6.1	9.3	1.6		1.6
22 July	Barge	0.065	0	0.065	0.0325	0.0316	0.0009
Test site: Enewetak, Pacific							
1948: 14 April	Tower	0.037	0	0.037	0.019	0.018	
30 April	Tower	0.049	0	0.049	0.025	0.024	
14 May	Tower	0.018	0	0.018	0.009	0.009	
1951: 7 April	Tower	0.081	0	0.081	0.041	0.039	0.001
20 April	Tower	0.047	0	0.047	0.024	0.023	
8 May	Tower	0.15	0.075	0.225	0.075	0.066	0.009
24 May	Tower	0.0455	0	0.0455	0.0228	0.0227	
1952: 31 October	Surface	5.7 [d]	4.7	10.4	2.85		2.85
15 November	Air drop	0.25	0.25	0.5		0.2	0.05
1954: 13 May	Barge	0.845	0.845	1.69	0.423	0.164	0.258
1956: 4 May	Surface	0.04	0	0.04	0.02	0.02	
27 May	Tower	0.00019	0	0.00019	0.000095	0.000095	
30 May	Tower	0.0149	0	0.0149	0.00745	0.00745	
6 June	Surface	0.0137	0	0.0137	0.00685	0.00685	
11 June	Tower	0.008	0	0.008	0.004	0.004	
13 June	Tower	0.00149	0	0.00149	0.000745	0.000745	
16 June	Air drop	0.0017	0	0.0017		0.0017	
21 June	Tower	0.0152	0	0.0152	0.0076	0.0076	
2 July	Tower	0.24	0.12	0.36	0.12	0.10	0.020
8 July	Barge	0.925	0.925	1.85	0.463	0.153	0.309
21 July	Barge	0.167	0.083	0.25	0.084	0.074	0.009
1958: 5 May	Surface	0.018	0	0.018	0.009	0.009	
11 May	Barge	0.081	0	0.081	0.041	0.0388	0.0012
12 May	Surface	0.685	0.685	1.37	0.343	0.175	0.167
16 May	Under water	0.009	0	0.009	0.0045	0.0045	
20 May	Barge	0.0059	0	0.0059	0.003	0.0029	
26 May	Barge	0.22	0.11	0.33	0.11	0.094	0.016
26 May	Barge	0.057	0	0.057	0.0285	0.0278	0.0007
30 May	Barge	0.0116	0	0.0116	0.0058	0.0058	
2 June	Barge	0.015	0	0.015	0.0075	0.0075	
8 June	Under water	0.008	0	0.008	0.004	0.004	
14 June	Barge	0.725	0.725	1.45	0.363	0.174	0.188
18 June	Barge	0.011	0	0.011	0.0055	0.0055	
27 June	Barge	0.44	0.44	0.88	0.22	0.151	0.069
28 June	Barge	3 [d]	5.9	8.9	1.5		1.5
1 July	Barge	0.0052	0	0.0052	0.0026	0.0026	
5 July	Barge	0.265	0.132	0.397	0.133	0.109	0.024
17 July	Barge	0.170	0.085	0.255	0.085	0.074	0.011
22 July	Barge	0.135	0.067	0.202	0.067	0.060	0.007
26 July	Barge	1	1	2	0.5	0.138	0.363
6 August	Surface	0	0	0	0	0	
18 August	Surface	0.00002	0	0.00002	0.00001	0.00001	

Table 1 (continued)

Date	*Type of test*	*Yield (Mt)* [a]			*Partitioned fission yield (Mt)*		
		Fission	*Fusion*	*Total*	*Local and regional*	*Troposphere*	*Stratosphere*
Test site: Pacific							
1955: 14 May	Under water	0.03	0	0.03	0.015	0.015	
1958: 28 April	Balloon	0.0017	0	0.0017		0.0017	
1962: 5 May	Rocket	0.05	0	0.05 [c]			0.05
11 May	Under water	0.02	0	0.02 [c]	0.01	0.01	
Test site: Atlantic, 38°–50°S							
1958: 27 August	Rocket	0.0015	0	0.0015			0.0015
30 August	Rocket	0.0015	0	0.0015			0.0015
6 September	Rocket	0.0015	0	0.0015			0.0015
Test site: Johnston Island, Pacific							
1958: 1 August	Rocket	1.9	1.9	3.8			1.9
12 August	Rocket	1.9	1.9	3.8			1.9
1962: 9 July	Rocket	0.7	0.7	1.4			0.7
2 October	Air drop	0.075	0	0.075		0.073	0.002
6 October	Air drop	0.0113	0	0.0113		0.0113	
18 October	Air drop	0.795	0.795	1.59		0.341	0.454
20 October	Rocket	0.02	0	0.02 [c]			0.02
26 October	Rocket	0.25	0.25	0.5 [c]			0.25
27 October	Air drop	0.4	0.4	0.8		0.285	0.115
30 October	Air drop	4.15	4.15	8.3			4.15
1 November	Rocket	0.25	0.25	0.5 [c]			0.25
4 November	Rocket	0.02	0	0.02 [c]			0.02
Test site: Christmas Island, Pacific							
1962: 25 April	Air drop	0.127	0.063	0.19		0.114	0.014
27 April	Air drop	0.27	0.14	0.41		0.226	0.047
2 May	Air drop	0.545	0.545	1.09		0.336	0.209
4 May	Air drop	0.335	0.335	0.67		0.252	0.083
8 May	Air drop	0.1	0	0.1		0.097	0.003
9 May	Air drop	0.1	0	0.1		0.097	0.003
11 May	Air drop	0.05	0	0.05		0.049	0.001
12 May	Air drop	0.25	0.25	0.5		0.2	0.05
14 May	Air drop	0.097	0	0.097		0.094	0.003
19 May	Air drop	0.073	0	0.073		0.071	0.002
25 May	Air drop	0.0026	0	0.0026		0.0026	
27 May	Air drop	0.043	0	0.043		0.043	
8 June	Air drop	0.391	0.391	0.782		0.281	0.110
9 June	Air drop	0.14	0.07	0.21		0.124	0.016
10 June	Air drop	1.5	1.5	3		0.12	1.38
12 June	Air drop	0.6	0.6	1.2		0.345	0.255
15 June	Air drop	0.4	0.4	0.8		0.28	0.12
17 June	Air drop	0.052	0	0.052		0.051	0.001
19 June	Air drop	0.0022	0	0.0022		0.0022	
22 June	Air drop	0.0815	0	0.0815		0.0791	0.0024
27 June	Air drop	3.83	3.82	7.65			3.83
30 June	Air drop	0.63	0.64	1.27		0.346	0.284
10 July	Air drop	0.5	0.5	1		0.325	0.175
11 July	Air drop	1.94	1.94	3.88		0.089	1.851

USSR

Date	*Type of test*	*Yield (Mt)* [a]			*Partitioned fission yield (Mt)*		
		Fission	*Fusion*	*Total*	*Local and regional*	*Troposphere*	*Stratosphere*
Test site: Semipalatinsk							
1949: 29 August	Surface	0.022	0	0.022	0.011	0.011	
1951: 24 September	Surface	0.038	0	0.038	0.019	0.018	0.001
18 October	Air	0.042	0	0.042		0.039	0.003
1953: 12 August	Surface	0.04	0.36	0.4 [e]	0.02	0.0089	0.011
23 August	Air	0.028	0	0.028		0.028	
3 September	Air	0.0058	0	0.0058		0.0058	

Table 1 (continued)

Date	*Type of test*	*Yield (Mt)* [a]			*Partitioned fission yield (Mt)*		
		Fission	*Fusion*	*Total*	*Local and regional*	*Troposphere*	*Stratosphere*
1953: 8 September	Air	0.0016	0	0.0016		0.0016	
10 September	Air	0.0049	0	0.0049		0.0049	
1954: 29 September	Air	0.0002	0	0.0002		0.0002	
1 October	Air	0.00003	0	0.00003		0.00003	
3 October	Air	0.002	0	0.002		0.002	
5 October	Surface	0.004	0	0.004	0.002	0.002	
8 October	Air	0.0008	0	0.0008		0.0008	
19 October	Surface	0.000001	0	0.000001	0.0000005	0.0000005	
23 October	Air	0.062	0	0.062		0.054	0.008
26 October	Air	0.0028	0	0.0028		0.0028	
30 October	Surface	0.01	0	0.01	0.005	0.005	
1955: 29 July	Surface	0.0013	0	0.0013	0.00065	0.00065	
2 August	Surface	0.012	0	0.012	0.006	0.006	
5 August	Surface	0.0012	0	0.0012	0.0006	0.0006	
6 November	Air	0.167	0.083	0.25		0.106	0.061
22 November	Air	0.8	0.8	1.6		0.003	0.797
1956 16 March	Surface	0.014	0	0.014	0.007	0.007	
25 March	Surface	0.0055	0	0.0055	0.00275	0.00275	
24 August	Surface	0.027	0	0.027	0.0135	0.0135	
30 August	Air	0.45	0.45	0.9		0.020	0.430
2 September	Air	0.051	0	0.051		0.046	0.005
10 September	Air	0.038	0	0.038		0.036	0.002
17 November	Air	0.45	0.45	0.9		0.020	0.430
14 December	Air	0.04	0	0.04		0.037	0.003
1957: 8 March	Air	0.019	0	0.019		0.019	
3 April	Air	0.042	0	0.042		0.039	0.003
6 April	Air	0.057	0	0.057		0.050	0.007
10 April	High atmosphere	0.34	0.34	0.68			0.34
12 April	Air	0.022	0	0.022		0.022	
16 April	Air	0.213	0.107	0.32		0.115	0.098
22 August	Air	0.26	0.26	0.52		0.078	0.182
26 August	Air	0.0001	0	0.0001		0.0001	
13 September	Air	0.0059	0	0.0059		0.0059	
26 September	Air	0.013	0	0.013		0.013	
28 December	Air	0.012	0	0.012		0.012	
1958: 4 January	Air	0.0013	0	0.0013		0.0013	
17 January	Air	0.0005	0	0.0005		0.0005	
13 March	Air	0.0012	0	0.0012		0.0012	
14 March	Air	0.035	0	0.035		0.033	0.002
15 March	High atmosphere	0.014	0	0.014			0.014
18 March	Air	0.00016	0	0.00016		0.00016	
20 March	High atmosphere	0.012	0	0.012			0.012
22 March	Air	0.018	0	0.018		0.018	
1961: 1 September	Air	0.016	0	0.016		0.016	
4 September	Air	0.009	0	0.009		0.009	
5 September	Air	0.016	0	0.016		0.016	
6 September	Air	0.0011	0	0.0011		0.0011	
9 September	Surface	0.00038	0	0.00038	0.00019	0.00019	
10 September	Air	0.00088	0	0.00088		0.00088	
11 September	Air	0.0003	0	0.0003		0.0003	
13 September	Air	0.004	0	0.004 [f]		0.004	
14 September	Surface	0.0004	0	0.0004	0.0002	0.0002	
17 September	Air	0.04	0	0.04 [f]		0.037	
18 September	Surface	0.000004	0	0.000004	0.000002	0.000002	
18 September	Air	0.00075	0	0.00075		0.00075	
19 September	Surface	0.00003	0	0.00003	0.000015	0.000015	
20 September	Air	0.0048	0	0.0048		0.0048	
21 September	Air	0.0008	0	0.0008		0.0008	
26 September	Air	0.0012	0	0.0012		0.0012	
1 October	Air	0.003	0	0.003		0.003	
4 October	Air	0.013	0	0.013		0.013	
12 October	Air	0.015	0	0.015		0.015	
17 October	Air	0.0066	0	0.0066		0.0066	
19 October	Air	0.004	0	0.004 [e]		0.004	
25 October	Air	0.0005	0	0.0005		0.0005	0.003
30 October	Air	0.00009	0	0.00009		0.00009	
1 November	Air	0.0027	0	0.0027		0.0027	
2 November	Air	0.0006	0	0.0006		0.0006	

Table 1 (continued)

Date	*Type of test*	*Yield (Mt)* [a]			*Partitioned fission yield (Mt)*		
		Fission	*Fusion*	*Total*	*Local and regional*	*Troposphere*	*Stratosphere*
1961: 3 November	Surface	0.000001	0	0.000001	0.0000005	0.0000005	
3 November	Air	0.0009	0	0.0009		0.0009	
4 November	Surface	0.0002	0	0.0002	0.0001	0.0001	
1962: 1 August	Air	0.0024	0	0.0024		0.0024	
3 August	Air	0.0016	0	0.0016		0.0016	
4 August	Air	0.0038	0	0.0038		0.0038	
7 August	Surface	0.0099	0	0.0099	0.00495	0.00495	
18 August	Air	0.0074	0	0.0074		0.0074	
18 August	Air	0.0058	0	0.0058		0.0058	
21 August	Air	0.04	0	0.04 [e]		0.037	0.003
22 August	Air	0.003	0	0.003		0.003	
23 August	Air	0.0025	0	0.0025		0.0025	
25 August	Air	0.004	0	0.004 [e]		0.004	
27 August	Air	0.011	0	0.011		0.011	
31 August	Air	0.0027	0	0.0027		0.0027	
22 September	Surface	0.00021	0	0.00021	0.00011	0.0001	
24 September	Air	0.0012	0	0.0012		0.0012	
25 September	Surface	0.007	0	0.007	0.0035	0.0035	
28 September	Air	0.0013	0	0.0013		0.0013	
9 October	Air	0.008	0	0.008		0.008	
10 October	Air	0.0092	0	0.0092		0.0092	
13 October	Air	0.0049	0	0.0049		0.0049	
14 October	Air	0.004	0	0.004 [e]		0.004	
20 October	Air	0.0067	0	0.0067		0.0067	
28 October	Air	0.0078	0	0.0078		0.0078	
28 October	Air	0.0078	0	0.0078		0.0078	
30 October	Surface	0.0012	0	0.0012	0.0006	0.0006	
31 October	Air	0.01	0	0.01		0.01	
1 November	Air	0.003	0	0.003		0.003	
3 November	Air	0.0047	0	0.0047		0.0047	
4 November	Air	0.0084	0	0.0084		0.0084	
5 November	Surface	0.0004	0	0.0004	0.0002	0.0002	
11 November	Surface	0.0001	0	0.0001	0.00005	0.00005	
13 November	Surface	0.000001	0	0.000001	0.0000005	0.0000005	
14 November	Air	0.012	0	0.012		0.012	
17 November	Air	0.018	0	0.018		0.018	
24 November	Surface	0.000001	0	0.000001	0.0000005	0.0000005	
26 November	Surface	0.000031	0	0.000031	0.000016	0.000015	
1 December	Air	0.0024	0	0.0024		0.0024	
23 December	Surface	0.000001	0	0.000001	0.0000005	0.0000005	
24 December	Surface	0.000007	0	0.000007	0.00000035	0.00000035	
24 December	Surface	0.000028	0	0.000028	0.000014	0.000014	
Test site: Novaya Zemlya							
1955: 21 September	Under water	0.0035	0	0.0035	0.00175	0.00175	
1957: 7 September	Surface	0.032	0	0.032	0.016	0.0154	0.0006
24 September	Air	0.8	0.8	1.6		0.003	0.797
6 October	Air	1.45	1.45	2.9			1.45
10 October	Under water	0.01	0	0.01	0.005	0.005	
1958: 23 February	Air	0.43	0.43	0.86		0.025	0.405
27 February	Air	0.163	0.087	0.25		0.103	0.060
27 February	Air	0.75	0.75	1.5		0.004	0.746
14 March	Air	0.04	0	0.04		0.037	0.003
21 March	Air	0.325	0.325	0.65		0.054	0.271
30 September	Air	0.6	0.6	1.2		0.005	0.595
30 September	Air	0.45	0.45	0.9		0.020	0.430
2 October	Air	0.193	0.097	0.29		0.112	0.071
2 October	Air	0.04	0	0.04		0.037	0.003
4 October	Air	0.009	0	0.009		0.009	
5 October	Air	0.015	0	0.015		0.015	
6 October	Air	0.0055	0	0.0055		0.0055	
10 October	Air	0.068	0	0.068		0.059	0.009
12 October	Air	0.725	0.725	1.45		0.004	0.721
15 October	Air	0.75	0.75	1.5		0.004	0.746
18 October	Air	1.45	1.45	2.9			1.45
19 October	Air	0.04	0	0.04		0.037	0.003
19 October	Air	0.000001	0	0.000001		0.000001	
20 October	Air	0.293	0.147	0.44		0.115	0.178
21 October	Air	0.002	0	0.002		0.002	

Table 1 (continued)

Date	*Type of test*	*Yield (Mt)* [a]			*Partitioned fission yield (Mt)*		
		Fission	*Fusion*	*Total*	*Local and regional*	*Troposphere*	*Stratosphere*
1958: 22 October	Air	1.4	1.4	2.8			1.4
24 October	Air	0.5	0.5	1		0.005	0.495
25 October	Air	0.127	0.063	0.19		0.090	0.037
25 October	Air	0.0001	0	0.0001		0.0001	
1961: 10 September	Air	1.35	1.35	2.7			1.35
10 September	Air	0.012	0	0.012		0.012	
12 September	Air	0.575	0.575	1.15		0.005	0.570
13 September	Air	0.006	0	0.006		0.006	
14 September	Air	0.6	0.6	1.2		0.005	0.595
16 September	Air	0.415	0.415	0.83		0.029	0.386
18 September	Air	0.5	0.5	1		0.005	0.495
20 September	Air	0.266	0.134	0.4 [e]		0.118	0.148
22 September	Air	0.173	0.087	0.26		0.107	0.066
2 October	Air	0.167	0.083	0.25		0.106	0.061
4 October	Air	2	2	4 [e]			2
6 October	Air	2	2	4			2
8 October	Air	0.015	0	0.015		0.015	
20 October	Air	0.725	0.725	1.45		0.004	0.721
23 October	Under water	0.0048	0	0.0048	0.0024	0.0024	
23 October	Air	4.17	8.33	12.5			4.17
25 October	Air	0.2	0.1	0.3		0.113	0.087
27 October	Water surface	0.016	0	0.016	0.008	0.008	
30 October	Air	1.5 [b]	48.5 [b]	50			1.5
31 October	Air	2.5	2.5	5			2.5
31 October	Air	0.267	0.133	0.4 [e]		0.118	0.149
2 November	Air	0.08	0.04	0.12		0.063	0.017
2 November	Air	0.187	0.093	0.28		0.111	0.076
4 November	Air	0.015	0	0.015		0.015	
4 November	Air	0.267	0.133	0.4 [e]		0.118	0.149
4 November	Air	0.006	0	0.006		0.006	
1962: 5 August	Air	7.03	14.07	21.1			7.03
10 August	Air	0.267	0.133	0.4 [f]		0.118	0.149
20 August	Air	1.4	1.4	2.8			1.4
22 August	Air	0.8	0.8	1.6		0.003	0.797
22 August	Water surface	0.006	0	0.006	0.003	0.003	
25 August	Air	2	2	4 [f]			2
27 August	Air	2.1	2.1	4.2			2.1
2 September	Air	0.08	0	0.08		0.067	0.013
8 September	Air	0.95	0.95	1.9		0.001	0.949
15 September	Air	1.55	1.55	3.1			1.55
16 September	Air	1.625	1.625	3.25			1.625
18 September	Air	0.675	0.675	1.35		0.004	0.671
19 September	Air	2	2	4 [f]			2
21 September	Air	1.2	1.2	2.4			1.2
25 September	Air	6.37	12.73	19.1			6.37
27 September	Air	8.07	16.13	24.2 [f]			8.07
7 October	Air	0.32	0	0.32		0.173	0.147
9 October	Air	0.015	0	0.015		0.015	
22 October	Air	4.1	4.1	8.2			4.1
27 October	Air	0.173	0.087	0.26		0.107	0.066
29 October	Air	0.24	0.12	0.36		0.118	0.122
30 October	Air	0.187	0.093	0.28		0.111	0.076
1 November	Air	0.16	0.08	0.24		0.104	0.056
3 November	Air	0.26	0.13	0.39		0.119	0.141
3 November	Air	0.045	0	0.045		0.041	0.004
18 December	Air	0.073	0.037	0.11		0.058	0.015
18 December	Air	0.069	0	0.069		0.059	0.010
20 December	Air	0.0083	0	0.0083		0.0083	
22 December	Air	0.0063	0	0.0063		0.0063	
23 December	Air	0.287	0.143	0.43		0.117	0.170
23 December	Air	0.0083	0	0.0083		0.0083	
23 December	Air	0.0024	0	0.0024		0.0024	
24 December	Air	0.55	0.55	1.1		0.005	0.545
24 December	Air	8.07	16.13	24.2			8.07
25 December	Air	1.55	1.55	3.1			1.55
25 December	Air	0.0085	0	0.0085		0.0085	

Table 1 (continued)

Date	*Type of test*	*Yield (Mt)* [a]			*Partitioned fission yield (Mt)*		
		Fission	*Fusion*	*Total*	*Local and regional*	*Troposphere*	*Stratosphere*
Test site: Totsk, Aralsk							
1954: 14 September	Air	0.04	0	0.04		0.037	0.003
1956: 2 February	Surface	0.0003	0	0.0003	0.00015	0.00015	
Test site: Kapustin Yar							
1957: 19 January	Air	0.01	0	0.01		0.01	
1958: 1 November	Air	0.01	0	0.01		0.01	
3 November	Air	0.01	0	0.01		0.01	
1961: 6 September	Air	0.011	0	0.011		0.011	
6 October	Air	0.04	0	0.04		0.037	0.003
27 October	High atmosphere	0.0012	0	0.0012			0.0012
27 October	High atmosphere	0.0012	0	0.0012			0.0012
1962: 22 October	High atmosphere	0.2	0.1	0.3			0.2
28 October	High atmosphere	0.2	0.1	0.3			0.2
1 November	High atmosphere	0.2	0.1	0.3			0.2

a Estimated fission and fusion yields unless otherwise indicated; reported total yields.
b Reported fission or fusion yield.
c Indefinite reported yield; value assigned as follows: low, 0.02 Mt; no indication, 0.05 Mt; submegatonne, 0.5 Mt.
d Fission yield arbitrarily adjusted to obtain agreement with reported total fission yields for test series: 1952–1954 = 37 Mt (36 Mt from >1 Mt events), 1956 = 9 Mt (8 Mt from >1 Mt events), 1957–1958 = 19 Mt (14 Mt from >1 Mt events) [D7].
e Thermonuclear explosion; fission yield estimated [G7].
f Indefinite reported yield; value assigned as follows: 0.000001–0.02 Mt, 0.004 Mt; 0.02–0.15 Mt, 0.04 Mt; 0.15–1.5 Mt, 0.4 Mt; 1.5–10 Mt, 4 Mt; >10 Mt, 24.2 Mt.

Note: The dates of tests have been reported as Greenwich Mean Time.

Table 2
Atmospheric nuclear tests at each test site

Test site	*Number of tests*	*Yield (Mt)*			*Partitioned fission yield (Mt)*		
		Fission	*Fusion*	*Total*	*Local and regional*	*Troposphere*	*Stratosphere*
China							
Lop Nor	22	12.2	8.5	20.72	0.15	0.66	11.40
France							
Algeria	4	0.073	0	0.073	0.036	0.035	0.001
Fangataufa	4	1.97	1.77	3.74	0.06	0.13	1.78
Mururoa	37	4.13	2.25	6.38	0.13	0.41	3.59
Total	45	6.17	4.02	10.20	0.23	0.57	5.37
United Kingdom							
Monte Bello Island	3	0.1	0	0.1	0.050	0.049	0.0007
Emu	2	0.018	0	0.018	0.009	0.009	0
Marilinga	7	0.062	0	0.062	0.023	0.038	0
Malden Island	3	0.69	0.53	1.22	0	0.56	0.13
Christmas Island	6	3.35	3.30	6.65	0	1.09	2.26
Total	21	4.22	3.83	8.05	0.07	1.76	2.39
United States							
New Mexico	1	0.021	0	0.021	0.011	0.010	0
Japan (combat use)	2	0.036	0	0.036	0	0.036	0
Nevada	86	1.05	0	1.05	0.28	0.77	0.004
Bikini	23	42.2	34.6	76.8	20.3	1.07	20.8
Enewetak	42	15.5	16.1	31.7	7.63	2.02	5.85
Pacific	4	0.102	0	0.102	0.025	0.027	0.050
Atlantic	3	0.0045	0	0.0045	0	0	0.005
Johnston Island	12	10.5	10.3	20.8	0	0.71	9.76
Christmas Island	24	12.1	11.2	23.3	0	3.62	8.45
Total	197	81.5	72.2	153.8	28.2	8.27	44.9
USSR							
Semipalatinsk	116	3.74	2.85	6.59	0.097	1.23	2.41
Novaya Zemlya	91	80.8	158.8	239.6	0.036	2.93	77.8
Totsk, Aralsk	2	0.040	0	0.040	0	0.037	0.003
Kapustin Yar	10	0.68	0.30	0.98	0	0.078	0.61
Total	219	85.3	162.0	247.3	0.13	4.28	80.8
All countries							
Total	543 [a]	189	251	440	29	16	145

a Includes 22 safety tests of the United States, 12 safety tests of the United Kingdom, and 5 safety tests of France not listed inTable 1.

Table 3
Estimated fission and fusion yields of atmospheric nuclear tests of total yields equal to or greater than 4 Mt

Date	*Designation*	*Type of test*	*Test site*	*Yield (Mt)*		
				Fission	*Fusion*	*Total*
China						
17 November 1976		Air	Lop Nor	2.2 [a]	1.8	4
United States						
28 February 1954	Bravo	Surface	Bikini	9.0 [b]	6.0	15
4 May 1954	Yankee	Barge	Bikini	9.0 [b]	4.5	13.5
26 March 1954	Romeo	Barge	Bikini	7.3 [b]	3.7	11
31 October 1952	Mike	Surface	Enewetak	5.7 [b]	5.7	10.4
12 July 1958	Poplar	Barge	Bikini	3.2 [b]	6.1	9.3
28 June 1958	Oak	Barge	Enewetak	3.0 [b]	5.9	8.9
30 October 1962	Housatonic	Air drop	Johnston Island	4.15	4.15	8.3
27 June 1962	Bighorn	Air drop	Christmas Island	3.83	3.82	7.65
25 April 1954	Union	Barge	Bikini	4.6 [b]	2.3	6.9
20 July 1956	Tewa	Barge	Bikini	2.3 [b]	2.7	5
10 July 1956	Navaho	Barge	Bikini	1.5 [b]	3.0	4.5
USSR						
30 October 1961	Test 130	Air	Novaya Zemlya	1.5 [c]	48.5	50
24 December 1962	Test 219	Air	Novaya Zemlya	8.07	16.13	24.2
5 August 1962	Test 147	Air	Novaya Zemlya	7.03	14.07	21.1
25 September 1962	Test 173	Air	Novaya Zemlya	6.37	12.73	19.1
27 September 1962	Test 174	Air	Novaya Zemlya	8.07	16.13	24.2 [d]
23 October 1961	Test 123	Air	Novaya Zemlya	4.17	8.33	12.5
22 October 1962	Test 183	Air	Novaya Zemlya	4.1	4.1	8.2
31 October 1961	Test 131	Air	Novaya Zemlya	2.5	2.5	5
27 August 1962	Test 160	Air	Novaya Zemlya	2.1	2.1	4.2
4 October 1961	Test 113	Air	Novaya Zemlya	2	2	4 [e]
6 October 1961	Test 114	Air	Novaya Zemlya	2	2	4
25 August 1962	Test 158	Air	Novaya Zemlya	2	2	4 [c]
19 September 1962	Test 168	Air	Novaya Zemlya	2	2	4 [c]
Total						
		25 tests		106	183	289

a Estimated from measured stratospheric inventories [L7, L8] and global deposition [F7].
b Fission yield arbitrarily adjusted to obtain agreement with reported total fission yields for test series: 1952–1954 = 37 Mt (36 Mt from >1 Mt events), 1956 = 9 Mt (8 Mt from >1 Mt events), 1957–1958 = 19 Mt (14 Mt from >1 Mt events) [D7].
c Officially reported value [M2].
d Reported yield: >10 Mt.
e Reported yield: 1.5–10 Mt.

Table 4
Annual fission and fusion yields of nuclear tests and atmospheric partitioning, all countries

Year	*Number of tests*	*Yield (Mt)*			*Partitioned fission yield (Mt)*		
		Fission	*Fusion*	*Total*	*Local and regional*	*Troposphere*	*Fission*
1945	3 [a]	0.057	0	0.057	0.011	0.046	0
1946	2	0.042	0	0.042	0.011	0.031	0
1947							
1948	3	0.10	0	0.10	0.053	0.051	0
1949	1	0.022	0	0.022	0.011	0.011	0
1950							
1951	18	0.51	0.08	0.59	0.18	0.32	0.014
1952	11	6.08	4.95	11.0	2.89	0.28	2.91
1953	18	0.35	0.36	0.71	0.099	0.24	0.013
1954	16	30.9	17.4	48.3	15.4	0.31	15.2
1955	20	1.18	0.88	2.06	0.10	0.22	0.86
1956	32	10.0	12.9	22.9	3.68	0.99	5.31
1957	46	5.25	4.37	9.64	0.14	1.61	3.50
1958	91	26.5	30.3	56.8	5.86	3.31	17.3
1959							
1960	3	0.072	0	0.072	0.036	0.035	0.0009
1961	59	18.2	68.3	86.5	0.011	1.15	17.1
1962	118	71.8	98.5	170.4	0.052	5.77	66.0
1963							
1964	1	0.02	0	0.02	0.010	0.010	0
1965	1	0.04	0	0.04	0	0.037	0.003
1966	8	0.94	0.20	1.14	0.28	0.41	0.25
1967	5	1.88	1.30	3.18	0.011	0.046	1.82
1968	6	4.16	3.44	7.60	0	0	4.16
1969	1	1.9	1.1	3	0		1.90
1970	9	3.38	2.40	5.78	0	0.095	3.28
1971	6	0.84	0.62	1.46	0.01	0.057	0.77
1972	5	0.13	0	0.13	0	0.11	0.02
1973	6	1.42	1.1	2.52	0	0.021	1.40
1974	8	0.75	0.46	1.21	0	0.19	0.56
1975							
1976	3	2.32	1.8	4.12	0.01	0.09	2.22
1977	1	0.02	0	0.02	0	0.02	0
1978	2	0.04	0	0.04	0.02	0.02	0
1979							
1980	1	0.5	0.1	0.6	0	0.11	0.39
Total							
Total	543 [b]	189	251	440	29	16	145
Total worldwide dispersion (troposphere and stratosphere)						160.5	
Total measured global deposition						155 [c]	

a Includes two cases of military combat use in Japan.
b Total includes additional 39 safety tests: 22 by the United States, 12 by the United Kingdom, and 5 by France.
c Inferred from ^{90}Sr measurements. Since radioactive decay of 2%–3% occurred prior to deposition of ^{90}Sr, the estimated dispersed amount (injection into atmosphere) would also be about 160 Mt.

Table 5
Empirical estimates of the partitioning of yields from atmospheric tests into the troposphere and stratosphere [P1]

Total yield (Mt)	*Partitioned yield (Mt)*					
	Equatorial airburst [a] (0 °–30 ° latitude)			*Polar airburst [b] (30 °–90 ° latitude)*		
	Troposphere	*Lower stratosphere*	*Upper stratosphere*	*Troposphere*	*Lower stratosphere*	*Upper stratosphere*
0.03	0.03	0		0.029	0.001	
0.05	0.049	0.001		0.045	0.005	
0.07	0.068	0.002		0.06	0.01	
0.1	0.097	0.003		0.08	0.02	
0.2	0.18	0.02		0.14	0.06	
0.3	0.26	0.04		0.17	0.13	
0.5	0.40	0.10		0.16	0.34	
0.7	0.52	0.18		0.08	0.62	
1	0.65	0.35		0.01	0.99	
2	0.55	1.45			1.6	0.4
3	0.24	2.76			1.45	1.55
5	0.02	4.43	0.55		0.95	4.05
7		4.97	2.03		0.56	6.44
10		5.25	4.75		0.06	9.94
20		3.00	17.0			20
30		2.1	27.9			30
50		0.5	49.5			50

a Atmospheric heights: Troposphere <17 km, lower stratosphere 17–24 km, upper stratosphere 24–50 km.
b Atmospheric heights: Troposphere <9 km, lower stratosphere 9–17 km, upper stratosphere 17–50 km.

Table 6
Estimated annual injections of nuclear debris into atmospheric regions [a]

Year	*Fission energy (Mt)*										
	High equatorial atmosphere		*Polar stratosphere north*		*Equatorial stratosphere north*		*Equatorial stratosphere south*		*Troposphere*		*Total*
	North	*South*	*Upper*	*Lower*	*Upper*	*Lower*	*Upper*	*Lower*	*North*	*South*	
1945									0.046		0.046
1946									0.031		0.031
1947											
1948									0.051		0.051
1949									0.011		0.011
1950											
1951				0.004		0.010			0.32		0.33
1952					1.35	1.55			0.27	0.013	3.19
1953						0.013			0.23	0.009	0.25
1954				0.011	7.95	7.26			0.31		15.5
1955			0.096	0.76					0.22		1.08
1956				0.44	0.27	4.61		0.0007	0.94	0.053	6.30
1957	0.34		0.80	1.46		0.48		0.43	0.87	0.74	5.11
1958	1.93	1.90	1.58	6.05	1.30	3.70		0.84	2.92	0.39	20.6
1959											
1960						0.0009			0.035		0.036
1961	0.002		11.0	6.14					1.15		18.25
1962	1.28	0.62	41.5	9.48	1.91	7.02	0.63	3.58	3.96	1.81	71.8
1963											
1964									0.010		0.010
1965				0.003					0.037		0.040
1966				0.13				0.12	0.19	0.21	0.66
1967					0.44	1.26		0.12	0.020	0.026	1.87
1968			0.78	0.73			1.09	1.56			4.16
1969			0.98	0.92							1.90
1970			0.98	0.92				1.38		0.095	3.38
1971								0.77	0.010	0.047	0.83
1972				0.02					0.10	0.011	0.13
1973					0.25	1.15				0.021	1.42
1974						0.24		0.32	0.065	0.12	0.75
1975											
1976			1.46	0.76					0.090		2.31
1977									0.020		0.02
1978									0.020		0.02
1979											
1980				0.39					0.11		0.5
Total											
North	3.84		59.2	28.2	13.5	27.3			12.1		144
South		2.52					1.72	9.12		3.55	16.9
Global	6.36		139						15.6		161

a Yields were partitioned according to values of Table 5. For sites at temperate locations (30°–60° latitude) and yields of 1–4 Mt, input to the upper stratospheric region was reduced by one half, essentially averaging equatorial and polar partitioning assumptions; polar partitioning was maintained for the tropospheric portion. For tests in June, July, and August, inputs from temperate sites were assumed to be to the equatorial atmosphere and from all other months to the polar atmosphere. Partitioning from equatorial sites (Christmas Island and high altitude tests at Johnston Island) were assumed equally divided between the northern and southern hemispheres.

Table 7
Annual concentrations in air and deposition amounts of ^{90}Sr produced in atmospheric nuclear testing

Year	*Average annual concentration in air of mid-latitudes (mBq m^{-3})*				*Annual hemispheric deposition (PBq)*				*Cumulative deposit (PBq)*		
	Northern hemisphere		*Southern hemisphere*		*Northern hemisphere*		*Southern hemisphere*		*North*	*South*	*Total*
	Calculated [a]	*Measured* [b]	*Calculated* [a]	*Measured* [c]	*Calculated* [a]	*Measured* [d]	*Calculated* [a]	*Measured* [d]	*Measured* [e]	*Measured* [e]	*Measured* [e]
1945	0.002		-		0.017		-		0.17	0.00	0.17
1946	0.002		-		0.13		-		0.29	0.00	0.29
1947	- [f]		-		0.00		-		0.29	0.00	0.29
1948	0.002		-		0.20		-		0.47	0.00	0.47
1949	0.001		-		0.04		-		0.50	0.00	0.50
1950	-		-		-		-		0.49	0.00	0.49
1951	0.014		-		1.16		-		1.61	0.00	1.61
1952	0.014		0.001		1.18		0.05		2.72	0.05	2.77
1953	0.061		0.009		5.00		0.71		7.52	0.75	8.27
1954	0.16		0.053		13.0		4.38		20.1	5.02	25.1
1955	0.24		0.055		19.4		4.55		38.5	9.35	47.8
1956	0.22		0.057		17.9		4.70		55.0	13.7	68.7
1957	0.22	0.23	0.072		17.6		6.34		70.9	19.6	90.4
1958	0.36	0.48	0.081	0.11	29.4	23.3	6.73	9.45	92.2	28.5	121
1959	0.33	0.72	0.061	0.074	27.2	38.9	4.82	6.84	128	34.5	163
1960	0.14	0.15	0.043	0.056	11.3	9.69	3.52	6.22	135	39.9	175
1961	0.14	0.17	0.030	0.075	11.5	13.0	2.49	6.44	145	45.3	190
1962	0.67	0.99	0.185	0.11	54.6	53.4	15.2	9.75	194	53.8	248
1963	1.41	2.17	0.139	0.16	115	97.0	11.5	11.4	285	63.8	349
1964	0.87	1.25	0.109	0.18	71.2	61.3	8.97	15.6	339	77.7	416
1965	0.40	0.45	0.073	0.16	32.9	28.6	6.02	13.2	359	88.9	448
1966	0.18	0.19	0.054	0.085	14.6	12.1	4.48	7.66	362	94.3	457
1967	0.086	0.075	0.036	0.050	7.00	6.24	2.99	4.07	360	96.1	456
1968	0.062	0.098	0.041	0.046	5.11	7.22	3.40	3.76	358	97.5	456
1969	0.078	0.070	0.051	0.089	6.34	5.45	4.20	5.21	355	100	455
1970	0.088	0.12	0.056	0.066	7.18	7.62	4.60	4.74	354	103	457
1971	0.090	0.11	0.049	0.078	7.37	6.97	4.04	5.56	353	106	458
1972	0.051	0.035	0.029	0.053	4.15	3.19	2.40	3.55	347	107	454
1973	0.026	0.018	0.018	0.024	2.17	1.18	1.46	1.13	340	105	445
1974	0.037	0.056	0.020	0.018	3.06	4.46	1.68	1.45	336	104	441
1975	0.020	0.032	0.012	0.019	1.67	2.16	0.99	1.27	331	103	433
1976	0.014	0.011	0.006	0.007	1.14	1.00	0.46	0.77	324	101	425
1977	0.052	0.032	0.003	0.003	4.25	3.01	0.27	0.81	319	100	418
1978	0.031	0.035	0.003	0.002	2.50	3.70	0.21	0.67	315	97.8	413
1979	0.014	0.011	0.002	0.002	1.11	1.16	0.15	0.39	308	95.8	404
1980	0.011	0.008	0.001	0.003	0.91	1.11	0.09	0.39	302	93.9	396
1981	0.015	0.019	0.001	0.002	1.23	1.85	0.07	0.29	297	92.0	387

Table 7 (continued)

Year	*Average annual concentration in air of mid-latitudes (mBq m^{-3})*				*Annual hemispheric deposition (PBq)*				*Cumulative deposit (PBq)*		
	Northern hemisphere		*Southern hemisphere*		*Northern hemisphere*		*Southern hemisphere*		*North*	*South*	*Total*
	Calculated [a]	*Measured* [b]	*Calculated* [a]	*Measured* [c]	*Calculated* [a]	*Measured* [d]	*Calculated* [a]	*Measured* [d]	*Measured* [e]	*Measured* [e]	*Measured* [e]
1982	0.003	0.005	-	0.002	0.30	0.47	0.055	0.22	289	90.3	379
1983	0.002	0.001	-	-	0.09	0.33	0.033	0.19	283	88.2	370
1984	-		-		0.04	0.27	0.017	0.11	276	86.1	362
1985	-		-		0.013	0.078	0.008	0.052	269	84.0	353
1986	-		-		0.005		0.004		263	82.0	344
1987	-		-		0.002		0.002		256	80.0	336
1988	-		-		0.001		-		250	78.1	328
1989	-				-		-		244	76.2	320
1990	-		-		-		-		238	74.4	313
1991	-		-		-		-		233	72.6	305
1992	-		-		-		-		227	70.9	298
1993	-		-		-		-		222	69.2	291
1994	-		-		-		-		216	67.5	284
1995	-		-		-		-		211	65.9	277
1996	-		-		-		-		206	64.3	270
1997	-		-		-		-		201	62.8	264
1998	-		-		-		-		196	61.3	258
1999	-		-		-		-		192	59.8	251
2000	-		-		-		-		187	58.4	245
Total [g]	6.1 mBq a m^{-3}	8.9 mBq a m^{-3}	1.3 mBq a m^{-3}	1.7 mBq a m^{-3}	499 PBq	470 PBq 460 PBq [h]	111 PBq	142 PBq 144 PBq [h]			

a Annual average of monthly calculated value.
b Average of measurements performed monthly at Washington, D.C., and Miami (1957-1962), at New York City, Miami, and Sterling, Virginia (1963-1973) and at New York City and Miami (1974-1963) [F4, L6].
c Average of measurements performed monthly at Antofagasta and Santiago, Chile (1958-1976) and at Lima, Peru and Santiago, Chile (1977-1983) [F4, L6].
d Measured in global monitoring network [L9, V2].
e Calculated from decayed monthly measured deposition; prior to 1958 only calculated monthly deposition values are available.
f Less than 0.001 mBq m^{-3} or 0.001 PBq.
g Measured values included preferentially in total.
h Previously derived value based on measured cumulative deposition prior to 1958 [U6].

Table 8
Latitudinal distribution of radionuclide deposition from atmospheric nuclear testing based on measurements of ^{90}Sr [a]

Latitude band (degrees)	*Area of band (10^{12} m^2)*	*Population distribution (%)*	*Integrated deposition of ^{90}Sr (PBq)*	*Fractional deposition in band*	*Deposition density per unit deposition (Bq m^{-2} per PBq)*	*Latitudinal value relative to hemispheric value*
Northern hemisphere						
80–90	3.9	0	1	0.002	0.56	0.12
70–80	11.6	0	7.9	0.017	1.48	0.32
60–70	18.9	0.4	32.9	0.071	3.78	0.81
50–60	25.6	13.7	73.9	0.161	6.27	1.35
40–50	31.5	15.5	101.6	0.221	7.01	1.51
30–40	36.4	20.4	85.3	0.185	5.09	1.09
20–30	40.2	32.7	71.2	0.155	3.85	0.83
10–20	42.8	11	50.9	0.111	2.58	0.56
0–10	44.1	6.3	35.7	0.078	1.76	0.38
Total	255	100	460	1.0		
Population-weighted value [b]					4.65	1.00
Southern hemisphere						
80–90	3.9	0	0.3	0.002	0.53	0.14
70–80	11.6	0	2.5	0.017	1.50	0.40
60–70	18.9	0	6.7	0.046	2.46	0.66
50–60	25.6	0.5	12.1	0.084	3.28	0.88
40–50	31.5	0.9	28.1	0.195	6.19	1.65
30–40	36.4	13	27.6	0.191	5.26	1.40
20–30	40.2	14.9	28.1	0.195	4.85	1.29
10–20	42.8	16.7	17.8	0.123	2.89	0.77
0–10	44.1	54	21	0.146	3.30	0.88
Total	255	100	144	1.0		
Population-weighted value [c]					3.74	1.00

a Distributions valid only for long-lived radionuclides where majority of fallout is from debris originally injected into the stratosphere.
b Valid only for long-lived radionuclides. Value of 4.0 used for radionuclides with half-lives less than 100 d to reflect greater proportion of fallout from debris injected into the troposphere at low latitudes.
c Valid only for long-lived radionuclides. Value of 6.7 and 5.7 used for nuclides with half-lives less than 30 d and 30–100 d, respectively, to reflect greater proportion of fallout from debris injected into the troposphere at low latitudes.

Table 9
Radionuclides produced and globally dispersed in atmospheric nuclear testing

Radionuclide	*Half-life*	*Fission yield (%)*	*Normalized production* [a] *(PBq Mt^{-1})*	*Global release* [b] *(PBq)*
^{3}H	12.33 a		740 [c, d]	186 000 [f]
^{14}C	5 730 a		0.85 [c, e]	213 [f]
^{54}Mn	312.3 d		15.9 [c]	3 980
^{55}Fe	2.73 a		6.1 [c]	1 530
^{89}Sr	50.53 d	3.17	730	117 000
^{90}Sr	28.78 a	3.50	3.88	622
^{91}Y	58.51 d	3.76	748	120 000
^{95}Zr	64.02 d	5.07	921	148 000
^{103}Ru	39.26 d	5.20	1 540	247 000
^{106}Ru	373.6 d	2.44	76.0	12 200
^{125}Sb	2.76 a	0.40	4.62	741
^{131}I	8.02 d	2.90	4 210	675 000
^{140}Ba	12.75 d	5.18	4 730	759 000
^{141}Ce	32.50 d	4.58	1 640	263 000
^{144}Ce	284.9 d	4.69	191	30 700
^{137}Cs	30.07 a	5.57	5.90	948
^{239}Pu	24 110 a			6.52 [g]
^{240}Pu	6 563 a			4.35 [g]
^{241}Pu	14.35 a			142 [g]

a For fission products, the value is 1.45 10^{26} fissions per Mt times the fission yield times the decay constant (ln2 / half-life) divided by 3.15 10^{7} s a^{-1}.
b Corresponds to total globally dispersed fission energy of atmospheric tests of 160.5 Mt or fusion energy of 250.6 Mt (excludes releases associated with local and regional deposition).
c Estimate of Miskel [M3].
d Production per unit fusion energy of atmospheric tests.
e Estimated from total production up to 1972 [U6] and present data on fusion yields.
f Because of mobility and half-lives of ^{3}H and ^{14}C, the release is associated with a total fusion energy of 251 Mt.
g Estimated from ratios to ^{90}Sr in global deposition.

Table 10
Annual deposition of radionuclides produced in atmospheric nuclear testing

Year	Annual deposition (PBq) [a]													
	^{131}I	^{140}Ba	^{141}Ce	^{103}Ru	^{89}Sr	^{91}Y	^{95}Zr	^{144}Ce	^{54}Mn	^{106}Ru	^{125}Sb	^{55}Fe	^{90}Sr	^{137}Cs
Northern hemisphere														
1945	13.7	24.3	15.8	18.2	9.23	11.9	14.0	6.95	0.00	3.19	0.20	0.00	0.18	0.26
1946	9.82	17.2	10.3	12.6	6.39	8.24	9.19	4.70	0.00	2.28	0.15	0.00	0.13	0.19
1947	- [b]	-	-	0.011	0.011	0.019	0.023	0.050	0.00	0.029	0.002	0.00	0.002	0.003
1948	15.9	28.0	10.1	20.6	10.5	13.5	8.91	4.48	0.00	3.67	0.24	0.00	0.202	0.30
1949	3.34	5.95	2.15	4.40	2.23	2.86	1.89	0.93	0.00	0.76	0.049	0.00	0.042	0.062
1950	-	-	0.01	0.028	0.023	0.038	0.028	0.040	0.00	0.035	0.003	0.00	0.002	0.004
1951	96.5	171	88.8	124	62.7	80.5	76.8	37.1	0.24	21.2	1.35	0.10	1.16	1.73
1952	90.5	165	107	123	62.4	80.2	92.3	45.0	2.39	21.4	1.37	0.95	1.18	1.77
1953	69.5	129	98.3	143	84.4	119	118	103	5.80	72.4	5.35	2.89	5.00	7.50
1954	144	322	240	437	253	350	284	231	12.1	183	13.7	6.08	13.0	19.5
1955	70.1	127	71.5	97.8	55.5	80.4	79.6	193	9.13	182	17.7	6.51	19.4	29.1
1956	303	556	300	489	263	350	322	263	21.1	178	16.1	11.3	17.9	26.9
1957	278	511	412	434	234	314	421	355	25.0	186	16.2	14.6	17.6	26.5
1958	961	1 780	1 110	1 550	822	1089	1 136	791	57.7	417	30.5	28.6	23.3	34.9
1959	0.25	5.31	79.1	128	109	182	264	572	52.3	299	26.0	31.4	38.9	58.4
1960	10.4	18.4	6.66	13.7	7.19	9.84	7.84	97.5	9.85	65.2	8.61	10.4	9.69	14.5
1961	395	740	593	619	319	4 14	547	297	19.0	130	10.5	10.9	13.0	19.5
1962	1 260	2 320	1 960	2 110	1 160	1 580	2 160	1 790	299	777	57.3	158	53.4	80.1
1963	40.7	124	435	627	501	825	1 270	2 820	408	1 310	112	265	97.0	146
1964	3.04	5.39	2.07	4.76	4.85	11.7	21.6	791	131	447	56.5	138	61.3	91.9
1965	11.0	19.7	14.5	15.0	7.71	10.0	13.3	162	27.9	110	20.9	50.2	28.6	42.9
1966	46.5	81.9	60.4	62.4	32.1	41.6	55.2	57.3	6.44	35.8	7.77	17.1	12.1	18.2
1967	18.5	37.1	38.7	43.7	25.3	35.1	48.4	45.2	3.08	22.4	3.55	6.34	6.24	9.36
1968	2.99	6.61	7.85	9.97	7.37	12.2	18.8	59.1	3.83	29.0	3.26	4.03	7.22	10.8
1969	11.4	33.7	68.9	85.9	55.8	82.1	117	143	11.0	64.4	5.46	6.47	5.45	8.17
1970	5.88	16.8	33.4	43.5	30.7	47.8	70.9	145	8.54	68.8	6.31	5.84	7.62	11.4
1971	3.13	6.27	18.0	29.5	24.0	39.7	59.1	142	7.88	68.4	6.46	5.47	6.97	10.5
1972	30.3	54.5	41.1	43.3	22.7	30.1	40.2	54.9	2.25	28.1	3.18	2.35	3.19	4.78
1973	2.40	6.84	13.4	16.5	10.4	15.0	21.2	26.1	1.74	12.9	1.51	1.42	1.18	1.77
1974	20.2	36.6	29.4	32.1	18.6	26.6	37.7	62.1	4.55	29.1	2.66	2.81	4.46	6.69
1975	-	0.01	0.58	1.09	1.14	2.12	3.46	20.2	1.52	10.7	1.26	1.33	2.16	3.23
1976	34.0	63.0	45.2	48.2	24.4	31.3	39.5	22.6	0.61	10.4	0.93	0.57	1.00	1.50
1977	6.70	15.3	36.5	49.4	35.6	55.4	81.6	122	8.24	54.4	4.29	4.41	3.01	4.51
1978	5.53	9.23	3.04	6.10	3.19	4.38	3.70	32.2	2.34	17.9	2.06	2.12	3.70	5.55
1979	0.47	1.45	0.91	2.00	1.08	1.45	0.98	6.40	0.48	4.38	0.74	0.75	1.16	1.74
1980	35.6	65.4	49.7	51.0	25.9	33.3	43.9	22.2	0.42	9.47	0.78	0.38	1.11	1.67
1981	0.023	0.52	6.87	10.4	8.19	13.2	19.8	32.1	0.58	14.4	1.18	0.37	1.65	2.47
1982	-	-	0.0005	0.003	0.011	0.038	0.083	3.04	0.120	1.69	0.22	0.077	0.47	0.71
1983	-	-	-	-	-	0.0002	0.0005	0.37	0.025	0.25	0.054	0.019	0.33	0.5
1984	-	-	-	-	-	-	-	0.051	0.0050	0.043	0.014	0.0054	0.27	0.41
1985	-	-	-	-	-	-	-	0.0074	0.0010	0.008	0.0039	0.0015	0.078	0.12
1986	-	-	-	-	-	-	-	0.0011	0.0001	0.002	0.0011	0.0004	0.0053	0.0081

Table 10 (continued)

Year	Annual deposition (PBq) [a]													
	^{131}I	^{140}Ba	^{141}Ce	^{103}Ru	^{89}Sr	^{91}Y	^{95}Zr	^{144}Ce	^{54}Mn	^{106}Ru	^{125}Sb	^{55}Fe	^{90}Sr	^{137}Cs
Northern hemisphere (continued)														
1987	-	-	-	-	-	-	-	0.0002	-	0.0004	0.0003	0.0001	0.0023	0.0035
1988	-	-	-	-	-	-	-	-	-	-	-	-	0.0011	0.0016
1989	-	-	-	-	-	-	-	-	-	-	-	-	0.0005	0.0008
1990	-	-	-	-	-	-	-	-	-	-	-	-	0.0003	0.0005
1991	-	-	-	-	-	-	-	-	-	-	-	-	0.0002	0.0003
1992	-	-	-	-	-	-	-	-	-	-	-	-	0.0001	0.0002
1993	-	-	-	-	-	-	-	-	-	-	-	-	-	0.0001
1994	-	-	-	-	-	-	-	-	-	-	-	-	-	-
1995	-	-	-	-	-	-	-	-	-	-	-	-	-	-
1996	-	-	-	-	-	-	-	-	-	-	-	-	-	-
1997	-	-	-	-	-	-	-	-	-	-	-	-	-	-
1998	-	-	-	-	-	-	-	-	-	-	-	-	-	-
1999	-	-	-	-	-	-	-		-	-	-	-	-	-
Total	4 000	7 500	6 000	7 500	4 300	6 000	7 500	9 560	1 144	4 892	446	797	474	706
Southern hemisphere														
1945	-	-	-	-	-	-	-	-	-	-	-	-	-	-
1946	-	-	-	-	-	-	-	-	-	-	-	-	-	-
1947	-	-	-	-	-	-	-	-	-	-	-	-	-	-
1948	-	-	-	-	-	-	-	-	-	-	-	-	-	-
1949	-	-	-	-	-	-	-	-	-	-	-	-	-	-
1950	-	-	-	-	-	-	-	-	-	-	-	-	-	-
1951	0.004	0.024	0.043	0.12	0.077	0.12	0.088	0.071	0.003	0.061	0.004	0.001	0.004	0.006
1952	4.33	7.72	2.73	6.04	2.99	4.14	2.75	1.12	0.009	0.92	0.059	0.004	0.051	0.077
1953	3.07	5.41	2.16	5.31	3.37	5.60	4.27	8.88	0.61	8.19	0.70	0.373	0.71	1.065
1954	1.39	9.48	24.51	73.2	51.5	85.1	62.4	66.5	3.21	59.0	4.55	1.72	4.38	6.57
1955	0.0001	-	0.116	0.74	1.23	3.15	2.97	33.2	1.69	35.1	3.89	1.44	4.55	6.83
1956	28.2	62.5	47.0	90.4	50.8	75.1	68.8	53.0	5.13	39.0	3.92	2.85	4.70	7.05
1957	251	442	273	343	172	240	282	140	10.5	73.0	5.91	5.39	6.34	9.51
1958	147	273	218	278	150	218	270	169	15.0	82.4	6.48	7.58	9.45	14.2
1959	0.0007	0.045	1.84	4.06	4.27	8.85	12.9	61.4	6.24	37.4	4.00	4.78	6.84	10.3
1960	0.0000	0.000	0.002	0.010	0.035	0.13	0.28	22.4	2.42	16.0	2.46	3.01	6.22	9.34
1961	0.012	0.060	0.16	0.212	0.13	0.19	0.27	7.79	0.88	6.39	1.43	1.80	6.44	9.66
1962	642	1 160	921	1 060	554	791	1 070	550	43.1	231	16.1	20.2	9.75	14.6
1963	0.0056	0.095	4.87	11.2	13.1	28.0	47.5	206	22.8	102	10.1	17.0	11.4	17.1
1964	0.0000	0.000	0.007	0.040	0.14	0.52	1.21	74.0	9.96	44.2	6.41	12.3	15.6	23.4
1965	0.0001	0.001	0.002	0.004	0.003	0.010	0.027	22.1	3.40	16.0	3.47	7.04	13.2	19.8
1966	74.0	130	58.3	102	50.9	70.6	60.1	30.8	1.78	20.8	2.66	3.76	7.66	11.5
1967	13.9	30.0	35.2	44.2	25.3	37.8	50.9	34.6	1.42	16.3	1.78	2.02	4.07	6.11
1968	14.09	40.8	68.9	87.5	51.1	76.9	107	75.8	3.42	33.2	2.74	2.25	3.76	5.65
1969	0.003	0.091	4.33	8.37	7.98	15.5	24.9	74.5	4.84	36.2	3.49	3.40	5.21	7.82
1970	40.5	81.7	88.9	109	62.1	92.7	129	102	6.73	46.2	4.04	4.16	4.74	7.11
1971	21.2	44.2	50.6	62.8	36.6	55.8	78.5	81.2	5.50	37.9	3.48	3.68	5.56	8.34

Table 10 (continued)

Year	Annual deposition (PBq) [a]													
	^{131}I	^{140}Ba	^{141}Ce	^{103}Ru	^{89}Sr	^{91}Y	^{95}Zr	^{144}Ce	^{54}Mn	^{106}Ru	^{125}Sb	^{55}Fe	^{90}Sr	^{137}Cs
Southern hemisphere (continued)														
1972	3.58	6.22	5.37	6.95	4.57	7.65	11.5	30.8	2.25	15.8	1.81	1.95	3.55	5.32
1973	11.0	23.4	25.0	30.0	16.4	23.9	32.7	22.9	1.37	10.7	1.09	1.06	1.13	1.70
1974	44.5	82.1	66.4	76.1	39.6	56.4	76.1	43.7	1.37	19.1	1.52	0.92	1.45	2.17
1975	0.0005	0.029	1.03	1.89	1.69	3.16	5.00	14.6	0.77	7.31	0.78	0.64	1.27	1.90
1976	0.0003	0.001	0.001	0.003	0.006	0.021	0.048	2.80	0.17	1.73	0.28	0.25	0.77	1.15
1977	0.0000	-	0.041	0.11	0.135	0.30	0.51	2.25	0.16	1.21	0.17	0.16	0.81	1.22
1978	0.0000	-	-	0.001	0.004	0.015	0.033	1.45	0.11	0.86	0.13	0.14	0.67	1.01
1979	0.0000	-	-	0.000	0.000	0.000	0.001	0.54	0.045	0.38	0.08	0.08	0.39	0.59
1980	0.0007	0.003	0.005	0.006	0.003	0.005	0.007	0.15	0.014	0.13	0.040	0.042	0.39	0.59
1981	-	-	0.010	0.024	0.032	0.071	0.12	0.56	0.013	0.29	0.039	0.024	0.29	0.43
1982	-	-	-		0.0023	0.0068	0.14	0.35	0.0078	0.19	0.029	0.013	0.22	0.33
1983	-	-	-	-	-	-	0.0003	0.11	0.0026	0.075	0.015	0.0060	0.19	0.28
1984	-	-	-	-	-	-	-	0.026	0.0006	0.021	0.0062	0.0023	0.11	0.17
1985	-	-	-	-	-	-	-	0.0005	0.0001	0.0050	0.0022	0.0008	0.052	0.077
1986	-	-	-	-	-	-	-	0.0009	-	0.0012	0.0008	0.0003	0.0036	0.0055
1987	-	-	-	-	-	-	-	0.0001	-	0.0002	0.0002	0.0001	0.0017	0.0026
1988	-	-	-	-	-	-	-	-	-	-	-	-	0.0008	0.0012
1989	-	-	-	-	-	-	-	-	-	-	-	-	0.0004	0.0006
1990	-	-	-	-	-	-	-	-	-	-	-	-	0.0002	0.0004
1991	-	-	-	-	-	-	-	-	-	-	-	-	0.0001	0.0002
1992	-	-	-	-	-	-	-	-	-	-	-	-	-	0.0001
1993	-	-	-	-	-	-	-	-	-	-	-	-	-	-
1994	-	-	-	-	-	-	-	-	-	-	-	-	-	-
1995	-	-	-	--	-	-	-	-	-	-	-	-	-	-
1996	-	-	-	-	-	-	-	-	-	-	-	-	-	-
1997	-	-	-	-	-	-	-	-	-	-	-	-	-	-
1998	-	-	-	-	-	-	-	-	-	-	-	-	-	-
1999	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Total	1 300	2 400	1 900	2 400	1 300	1 900	2 400	1 934	155	998	94	110	142	213
World														
1945	13.6	24.3	15.8	18.2	9.23	11.9	14.0	6.95	0	3.19	0.20	0	0.18	0.26
1946	9.82	17.2	10.3	12.6	6.39	8.24	9.20	4.70	0	2.28	0.15	0	0.13	0.19
1947	-	-	0.004	0.011	0.011	0.019	0.023	0.050	0	0.029	0.002	0	0.002	0.003
1948	15.9	28.0	10.0	20.6	10.4	13.5	8.91	4.48	0	3.67	0.24	0	0.20	0.30
1949	3.34	5.95	2.15	4.40	2.23	2.86	1.89	0.93	0	0.76	0.049	0	0.042	0.062
1950	-	-	0.009	0.028	0.023	0.038	0.028	0.040	0	0.035	0.003	0	0.002	0.004
1951	96.5	171	88.8	125	62.8	80.7	76.9	37.1	0.25	21.2	1.35	0.10	1.16	1.74
1952	94.9	172	109	129	65.4	84.4	95.0	46.1	2.40	22.3	1.43	0.96	1.23	1.84
1953	72.6	134	100	149	87.8	125	122	112	6.41	80.5	6.06	3.26	5.71	8.57
1954	145	331	265	510	304	435	346	298	15.3	242	18.3	7.80	17.4	26.1
1955	70.1	127	71.6	98.5	56.8	83.6	82.5	227	10.8	217	21.6	7.95	24.0	35.9
1956	331	618	347	579	314	426	391	317	26.3	217	20.0	14.1	22.6	33.9

Table 10 (continued)

Year	Annual deposition (PBq) [a]													
	^{131}I	^{140}Ba	^{141}Ce	^{103}Ru	^{89}Sr	^{91}Y	^{95}Zr	^{144}Ce	^{54}Mn	^{106}Ru	^{125}Sb	^{55}Fe	^{90}Sr	^{137}Cs
1957	529	953	685	777	406	554	702	495	35.6	259	22.1	20.0	24.0	36.0
1958	1 110	2 050	1 330	1 820	972	1 310	1 410	960	72.7	500	37.0	36.2	32.7	49.1
1959	0.25	5.35	81.0	132	113	191	277	633	58.6	336	37.0	36.2	45.8	68.6
1960	10.4	18.4	6.67	13.7	7.23	9.98	8.12	120	12.3	81.3	11.1	13.4	15.9	23.9
1961	395	740	593	619	319	414	548	305	19.9	136	11.9	12.7	19.4	29.2
1962	1 900	3 470	2 880	3 170	1 720	2 370	3 220	2 340	342	1 010	73.4	178	63.2	94.8
1963	40.7	124	440	638	514	853	1 310	3 030	430	1 420	122	282	108	163
1964	3.04	5.39	2.07	4.80	4.99	12.2	22.8	865	141	491	63.0	150	76.9	115
1965	11.0	19.7	14.5	15.0	7.71	10.0	13.3	184	31.3	126	24.3	57.3	41.8	62.7
1966	121	212	119	165	83.0	112	115	88.1	8.22	56.5	10.5	20.9	19.8	29.7
1967	32.4	67.1	73.9	87.9	50.6	72.9	99.3	79.7	4.50	38.7	5.33	8.36	10.3	15.5
1968	17.1	47.5	76.8	97.5	58.5	89.1	126	135	7.24	62.1	6.00	6.28	11.0	16.5
1969	11.4	33.8	73.2	94.3	63.8	97.5	142	217	15.9	101	8.95	9.87	10.7	16.0
1970	46.4	98.5	122	153	92.8	141	199	247	15.3	115	10.4	9.99	12.4	18.5
1971	24.4	50.5	68.6	92.4	60.7	95.4	138	223	13.4	106	9.94	9.15	12.5	18.8
1972	33.9	60.7	46.5	50.2	27.3	37.7	51.7	85.7	4.49	43.9	4.99	4.30	6.74	10.1
1973	13.4	30.2	38.4	46.4	26.8	39.0	54.0	49.1	3.11	23.7	2.60	2.48	2.31	3.47
1974	64.7	119	95.8	108	58.2	82.9	114	106	5.92	48.2	4.18	3.73	5.91	8.86
1975	0.001	0.039	1.61	2.98	2.82	5.28	8.46	34.8	2.29	18.0	2.04	1.98	3.42	5.13
1976	34.0	63.0	45.2	48.2	24.4	31.3	39.6	25.4	0.79	12.1	1.21	0.81	1.77	2.66
1977	6.71	15.3	36.5	49.5	35.8	55.7	82.1	124	8.40	55.6	4.45	4.58	3.82	5.73
1978	5.53	9.23	3.04	6.10	3.20	4.39	3.73	33.6	2.46	18.8	2.19	2.26	4.37	6.56
1979	0.47	1.45	0.92	2.00	1.08	1.45	0.98	6.94	0.53	4.77	0.82	0.84	1.55	2.33
1980	35.6	65.4	49.7	51.0	25.9	33.3	43.9	22.4	0.44	9.60	0.82	0.42	1.50	2.25
1981	0.023	0.518	6.88	10.4	8.22	13.3	19.9	32.6	0.59	14.7	1.22	0.39	1.93	2.90
1982	-	-	-	-	0.013	0.045	0.22	3.39	0.12	1.88	0.25	0.090	0.69	1.04
1983	-	-	-		-	-	0.001	0.48	0.026	0.33	0.07	0.025	0.52	0.78
1984	-	-	-	-	-	-	-	0.077	0.005	0.064	0.02	0.008	0.39	0.58
1985	-	-	-	-	-	-	-	0.008	0.001	0.013	0.006	0.002	0.13	0.19
1986	-	-	-	-	-	-	-	0.002	0.0001	0.003	0.002	0.001	0.0089	0.014
1987	-	-	-	-	-	-	-	0.0003	-	0.0002	0.0005	0.0001	0.0039	0.0060
1988	-	-	-	-	-	-	-	-	-	-	0.0002	-	0.0019	0.0029
1989	-	-	-	-	-	-	-	-	-	-	-	-	0.0010	0.0015
1990	-	-	-	-	-	-	-	-	-	-	-	-	0.0005	0.0008
1991	-	-	-	-	-	-	-	-	-	-	-	-	0.0003	0.0005
1992	-	-	-	-	-	-	-	-	-	-	-	-	0.0002	0.0003
1993	-	-	-	-	-	-	-	-	-	-	-	-	0.0001	0.0002
1994	-	-	-	-	-	-	-	-	-	-	-	-	-	0.0001
1995	-	-	-	-	-	-	-	-	-	-	-	-	-	-
1996	-	-	-	-	-	-	-	-	-	-	-	-	-	-
1997	-	-	-	-	-	-	-	-	-	-	-	-	-	-
1998	-	-	-	-	-	-	-	-	-	-	-	-	-	-
1999	-	-		-	-		-	-	-	-	-	-	-	-
Total	5 300	9 900	7 900	9 900	5 600	7 900	9 900	11 494	1 299	5 890	540	907	612	919

a Derived from estimated fission/fusion yields of tests with atmospheric model. Measured results used preferentially for ^{90}Sr and ^{137}Cs during 1958-1985. Model values for ^{131}I, ^{144}Ba, ^{141}Ce, ^{103}Ru, ^{89}Sr, ^{91}Y, and ^{95}Zr normalized to total hemispheric deposition estimated from available measurements. Latitudinal distributions for long-lived radionuclides may be estimated by use of parameters in Table 8.

b Indicates estimated value less than 0.0001 PBq.

Table 11
Population-weighted cumulative deposition density of radionuclides produced in atmospheric nuclear testing

Year	Cumulative deposition density (Bq m^{-2}) [a]													
	^{131}I	^{140}Ba	^{141}Ce	^{103}Ru	^{89}Sr	^{91}Y	^{95}Zr	^{144}Ce	^{54}Mn	^{106}Ru	^{125}Sb	^{55}Fe	^{90}Sr	^{137}Cs
Northern hemisphere														
1945	1.73	4.92	7.53	9.99	5.96	8.33	10.2	8.70	0.00	4.17	0.28	0.00	0.25	0.38
1946	1.17	3.31	5.28	7.84	5.27	7.99	10.1	21.7	0.00	11.4	0.96	0.00	0.96	1.44
1947	- [b]	-	0.22	0.61	0.72	1.43	1.96	17.0	0.00	10.4	1.15	0.00	1.36	2.05
1948	1.94	5.49	5.02	12.3	7.80	11.3	8.04	16.2	0.00	13.2	1.46	0.00	1.85	2.78
1949	0.43	1.21	1.02	2.51	1.73	2.76	2.10	12.1	0.00	11.8	1.58	0.00	2.25	3.39
1950	-	-	0.15	0.52	0.51	0.91	0.73	6.99	0.00	7.83	1.38	0.00	2.35	3.54
1951	12.2	33.7	36.9	63.1	38.5	54.7	51.3	57.2	0.49	39.5	3.61	0.23	4.62	6.95
1952	11.2	29.6	41.1	55.9	36.0	53.6	67.3	128	1.30	77.8	7.41	0.69	8.99	13.5
1953	9.33	30.6	70.9	119	87.5	139	155	362	20.2	251	23.	11.5	25.9	38.9
1954	18.2	65.0	121	261	187	289	255	637	36.2	526	52.7	25.8	61.4	92.2
1955	8.70	23.5	27.6	56.1	50.6	96.0	95.1	982	52.0	976	116	48.7	146	219
1956	38.0	111	151	285	186	276	276	1 050	68.4	1 020	152	71.1	222	333
1957	33.5	96.1	182	235	165	261	358	1 340	104	1 090	175	106	281	423
1958	121	356	522	869	568	845	944	2 340	179	1 570	234	172	368	554
1959	4.06	17.2	135	249	237	429	605	3 460	290	2 240	322	280	535	805
1960	1.31	3.69	3.57	9.38	8.97	20.0	30.6	2 100	197	1 560	306	288	604	910
1961	49.8	141	200	225	126	169	229	1 150	109	959	262	253	634	955
1962	155	449	896	1 140	774	1 180	1 730	3 940	625	2 100	341	548	795	1 200
1963	10.2	51.6	434	710	667	1 200	1 950	10 300	1 560	5 290	665	1 390	1 140	1 710
1964	0.38	1.05	1.75	7.18	19.4	60.8	133	8 740	1 430	5 250	849	1 890	1 480	2 220
1965	1.40	4.04	7.70	10.1	6.70	10.7	16.3	4 660	825	3 390	801	1 810	1 620	2 440
1966	5.39	15.3	28.0	34.4	22.0	32.1	45.8	2 170	407	1 910	673	1 530	1 670	2 520
1967	2.57	8.05	21.3	28.7	20.9	33.0	49.3	1 040	193	1 050	543	1 230	1 670	2 520
1968	0.65	2.02	5.53	8.78	8.68	16.7	28.0	619	98.8	633	435	972	1 660	2 510
1969	1.46	6.63	30.6	45.3	37.1	62.1	95.8	582	70.0	483	355	777	1 650	2 490
1970	0.74	3.23	16.8	27.1	25.5	46.6	76.3	693	61.5	475	301	629	1 640	2 480
1971	0.39	1.43	14.2	25.3	24.9	46.0	75.0	749	54.5	482	260	512	1 630	2 480
1972	3.88	11.3	21.8	28.3	19.4	30.4	44.3	566	37.1	388	221	412	1 620	2 460
1973	0.30	1.37	6.03	8.40	6.27	10.0	15.2	308	20.6	241	179	326	1 590	2 410
1974	2.58	7.35	15.3	20.5	15.6	25.9	40.2	302	21.9	211	148	263	1 560	2 380
1975	0.00	0.00	0.89	2.03	2.64	5.58	9.86	235	18.4	167	121	213	1 540	2 350
1976	4.08	11.4	15.2	18.3	10.4	14.3	18.0	134	10.2	107	98.6	168	1 510	2 300
1977	0.96	4.05	25.5	40.2	35.2	60.6	94.8	350	23.1	193	88.9	142	1480	2 260
1978	0.57	1.43	1.94	4.31	3.95	7.85	12.2	340	24.4	205	81.6	124	1470	2 240
1979	0.19	0.75	0.91	2.32	1.59	2.48	2.02	184	14.2	134	68.5	101	1 440	2 200
1980	4.50	12.6	16.6	18.3	9.94	13.2	17.8	94.4	7.14	78.7	55.1	80.4	1 410	2 160
1981	0.03	0.78	12.5	19.9	17.1	29.1	45.2	168	5.51	100	48.3	64.2	1 380	2 120
1982	-	-	0.005	0.032	0.11	0.39	0.165	69.0	2.45	50.8	37.4	49.9	1 350	2 080
1983	-	-	-	0.0001	0.001	0.005	0.0006	28.4	1.09	25.7	29.0	38.7	1 320	2 040
1984	-	-	-	-	-	-	-	11.7	0.48	13.0	22.5	30.1	1 290	1 990
1985	-	-	-	-	-	-	-	4.80	0.22	6.58	17.5	23.4	1 260	1 950
1986	-	-	-	-	-	-	-	1.97	0.10	3.33	13.6	18.1	1 230	1 900

Table 11 (continued)

Year	Cumulative deposition density (Bq m^{-2}) [a]													
	^{131}I	^{140}Ba	^{141}Ce	^{103}Ru	^{89}Sr	^{91}Y	^{95}Zr	^{144}Ce	^{54}Mn	^{106}Ru	^{125}Sb	^{55}Fe	^{90}Sr	^{137}Cs
Northern hemisphere (continued)														
1987	-	-	-	-	-	-	-	0.81	0.043	1.68	10.5	14.1	1 200	1 860
1988	-	-	-	-	-	-	-	0.33	0.019	0.85	8.16	10.9	1 170	1 820
1989	-	-	-	-	-	-	-	0.14	0.0084	0.43	6.33	8.49	1 150	1 780
1990	-	-	-	-	-	-	-	0.057	0.0038	0.22	4.91	6.60	1 120	1 740
1991	-	-	-	-	-	-	-	0.023	0.0017	0.11	3.81	5.12	1 090	1 700
1992	-	-	-	-	-	-	-	0.010	0.0007	0.056	2.96	3.98	1 070	1 660
1993	-	-	-	-	-	-	-	0.0039	0.0003	0.028	2.29	3.09	1 040	1 620
1994	-	-	-	-	-	-	-	0.0016	0.0001	0.014	1.78	2.40	1 020	1 580
1995	-	-	-	-	-	-	-	0.0007	0.0001	0.0072	1.38	1.86	991	1 550
1996	-	-	-	-	-	-	-	0.0003	-	0.0037	1.07	1.45	967	1 510
1997	-	-	-	-	-	-	-	0.0001	-	0.0019	0.83	1.12	944	1 480
1998	-	-	-	-	-	-	-	-	-	0.0009	0.64	0.87	921	1 440
1999	-	-	-	-	-	-	-	-	-	0.0005	0.50	0.68	899	1 410
Total [c]														
1945-1999	510	1 520	3 080	4 660	3 440	5 560	7 590	50 000	6 560	33 300	8 160	14 600	52 900	81 000
2000-2099										0.0003	1.75	2.3	33 900	55 300
2100-2199													3 000	5 550
2200-∞													292	620
1945-∞	510	1 520	3 080	4 660	3 440	5 560	7 590	50 000	6 560	33 300	8 160	14 600	90 000	142 000
Southern hemisphere														
1945	-	-	-	-	-	-	-	-	-	-	-	-	-	-
1946	-	-	-	-	-	-	-	-	-	-	-	-	-	-
1947	-	-	-	-	-	-	-	-	-	-	-	-	-	-
1948	-	-	-	-	-	-	-	-	-	-	-	-	-	-
1949	-	-	-	-	-	-	-	-	-	-	-	-	-	-
1950	-	-	-	-	-	-	-	-	-	-	-	-	-	-
1951	0.0009	0.008	0.029	0.095	0.073	0.12	0.093	0.072	0.003	0.064	0.005	0.001	0.004	0.007
1952	0.92	2.53	1.44	3.47	1.89	2.75	1.87	0.76	0.009	0.66	0.049	0.006	0.047	0.070
1953	0.65	1.83	1.70	5.09	4.03	7.43	5.95	11.5	0.66	10.8	0.97	0.43	1.01	1.51
1954	0.30	3.29	17.3	59.6	49.5	88.8	68.3	85.9	4.58	81.4	7.42	3.12	7.92	11.9
1955	-	0.001	1.09	7.01	11.6	29.1	27.0	175	9.1	186	21.1	8.19	25.4	38.1
1956	5.97	20.9	31.4	69.4	46.0	74.1	71.5	168	11.5	188	29.0	12.5	41.8	62.8
1957	50.1	137	163	248	155	246	296	289	23.8	232	36.1	21.5	57.0	85.7
1958	31.5	96.1	169	253	170	281	380	484	41.6	320	49.0	37.5	84.5	127
1959	0.85	3.23	25.1	51.2	50.4	101.1	151	540	50.9	358	58.9	53.3	117	177
1960	-	-	0.017	0.13	0.57	2.26	4.76	314	32.8	248	55.5	53.7	137	206
1961	0.002	0.02	0.059	0.080	0.055	0.12	0.24	165	18.7	155	49.6	49.9	156	235
1962	135	389	642	861	541	847	1 210	717	57.4	364	61.8	66.4	185	278
1963	0.006	0.17	31.3	78.5	99.6	221	382	1 290	118	672	94.9	118	219	330

Table 11 (continued)

Year	Cumulative deposition density (Bq m^{-2}) [a]													
	^{131}I	^{140}Ba	^{141}Ce	^{103}Ru	^{89}Sr	^{91}Y	^{95}Zr	^{144}Ce	^{54}Mn	^{106}Ru	^{125}Sb	^{55}Fe	^{90}Sr	^{137}Cs
Southern hemisphere (continued)														
1964	-	-	0.067	0.46	1.84	7.16	17.0	867	94.5	539	102	142	262	394
1965	-	-	0.002	0.0041	0.023	0.16	0.52	470	58.9	353	95.9	144	313	472
1966	15.6	43.1	35.2	67.2	37.9	56.0	51.6	245	32.4	218	83.9	130	341	514
1967	2.96	10.7	31.4	57.8	43.4	74.9	88.4	188	18.2	167	730	110	355	536
1968	2.99	13.6	39.8	57.0	39.3	65.4	96.8	178	12.4	134	62.5	91.5	359	542
1969	0.00	0.25	15.1	31.2	32.3	65.2	107	313	18.7	186	60.4	81.3	368	557
1970	8.59	27.6	58.6	81.6	53.8	86.9	127	305	20.3	187	57.8	74.1	377	571
1971	4.54	15.0	38.9	60.7	48.3	87.7	137	375	26.7	220	58.3	71.8	388	587
1972	0.73	2.08	8.12	15.3	15.3	31.0	51.7	306	22.8	191	54.8	65.9	396	601
1973	2.33	7.86	17.0	23.5	15.3	24.7	36.0	180	13.9	127	46.9	55.8	395	599
1974	9.46	27.7	44.1	58.6	36.9	58.6	84.7	147	9.49	99	40.2	46.4	389	591
1975	0.0014	0.120	6.84	13.9	13.9	27.7	45.3	150	7.49	95	35.8	39.0	386	587
1976	-	-	0.005	0.036	0.15	0.57	1.33	79.9	4.42	59.1	29.5	31.8	380	578
1977	-	-	0.028	0.084	0.13	0.31	0.56	37.8	2.31	33.2	23.6	25.3	374	570
1978	-	-	0.002	0.011	0.033	0.11	0.24	20.4	1.40	19.7	18.8	20.1	368	561
1979	-	-	-	0.000	0.0006	0.0036	0.0113	11.0	0.83	11.8	14.9	16.0	361	551
1980	0.0001	0.001	0.002	0.002	0.0011	0.0017	0.0026	5.32	0.44	6.63	11.8	12.7	353	541
1981	-	-	0.009	0.023	0.033	0.0780	0.1400	2.93	0.23	3.83	9.26	9.93	346	530
1982	-	-		-	-	0.0010	0.0005	1.20	0.10	1.94	7.19	7.71	339	520
1983	-	-	-	-	-	-	-	0.50	0.045	0.98	5.57	5.99	331	509
1984	-	-	-	-	-	-	-	0.20	0.020	0.50	4.32	4.65	324	498
1985	-	-	-	-	-	-	-	0.084	0.0089	0.25	3.36	3.61	317	487
1986	-	-	-	-	-	-	-	0.035	0.0040	0.13	2.60	2.80	309	476
1987	-	-	-	-	-	-	-	0.014	0.0018	0.064	2.02	2.18	302	466
1988	-	-	-	-	-	-	-	0.0058	0.0008	0.033	1.57	1.69	294	455
1989	-	-	-	-	-	-	-	0.0024	0.0003	0.017	1.22	1.31	287	445
1990	-	-	-	-	-	-	-	0.0010	0.0002	0.0083	0.94	1.02	281	435
1991	-	-	-	-	-	-	-	0.0004	0.0001	0.0042	0.73	0.79	274	425
1992	-	-	-	-	-	-	-	0.0002	-	0.0021	0.57	0.61	267	415
1993	-	-	-	-	-	-	-	0.0001	-	0.0011	0.44	0.48	261	406
1994	-	-	-	-	-	-	-	-	-	0.0005	0.34	0.37	255	396
1995	-	-	-	-	-	-	-	-	-	0.0003	0.27	0.29	249	387
1996	-	-	-	-	-	-	-	-	-	0.0001	0.21	0.22	243	379
1997	-	-	-	-	-	-	-	-	-	-	0.16	0.17	237	370
1998	-	-	-	-	-	-	-	-	-	-	0.12	0.13	231	362
1999	-	-	-	-	-	-	-	-	-	-	0.10	0.10	226	353
Total [c]														
1945-1999	273	808	1 380	2 100	1 470	2 490	7 130	8 120	714	5 470	1 380	1 630	12 600	19 200
2000-2099											0.40	0.30	8 480	13 400
2100-2199													752	1 390
2200-∞													73	155
1945-∞	273	808	1 380	2 100	1 470	2 490	7 130	8 120	714	5 470	1 380	1 630	21 900	35 000

Table 11 (continued)

Year	Cumulative deposition density (Bq m^{-2}) [a]													
	^{131}I	^{140}Ba	^{141}Ce	^{103}Ru	^{89}Sr	^{91}Y	^{95}Zr	^{144}Ce	^{54}Mn	^{106}Ru	^{125}Sb	^{55}Fe	^{90}Sr	^{137}Cs
World														
1945	1.54	4.38	6.70	8.89	5.31	7.41	9.06	7.74	-	3.71	0.25	-	0.22	0.33
1946	1.04	2.94	4.70	6.98	4.69	7.11	8.99	19.3	-	10.1	0.85	-	0.86	1.28
1947	-	-	0.20	0.54	0.64	1.27	1.74	15.1	-	9.24	1.03	-	1.21	1.82
1948	1.73	4.89	4.47	10.9	6.94	10.1	7.15	14.4	-	11.7	1.30	-	1.65	2.47
1949	0.38	1.07	0.91	2.24	1.54	2.45	1.87	10.8	-	10.5	1.40	-	2.01	3.02
1950	-	-	0.13	0.47	0.45	0.81	0.65	6.22	-	6.97	1.23	-	2.09	3.15
1951	10.9	30.0	32.9	56.1	34.2	48.7	45.7	50.9	0.44	35.2	3.22	0.21	4.11	6.19
1952	10.0	26.6	36.8	50.1	32.3	48.0	60.1	114	1.16	69.3	6.60	0.61	8.01	12.0
1953	8.38	27.4	63.3	107	78.3	124	139	323	18.0	224	20.7	10.3	23.2	34.8
1954	16.3	58.2	110	239	172	267	234	576	32.7	477	47.7	23.3	55.5	83.4
1955	7.74	20.9	24.7	50.7	46.3	88.7	87.6	893	47.2	889	106	44.3	133	199
1956	34.5	101	138	261	171	254	253	949	62.2	926	139	64.6	202	304
1957	35.3	101	180	236	164	259	352	1 230	95.0	992	160	96.7	257	386
1958	111	327	483	802	525	782	882	2 130	164	1 428	214	157	337	507
1959	3.71	15.7	123	228	216	393	555	3 140	263	2 030	293	255	489	736
1960	1.17	3.29	3.18	8.36	8.05	18.0	27.8	1 900	179	1 420	278	262	553	833
1961	44.3	125	178	200	112	151	204	1 040	99.5	871	239	230	581	876
1962	153	443	868	1 110	748	1 140	1 670	3 590	562	1 900	311	495	728	1 100
1963	9.11	45.9	390	641	604	1 090	1 770	9 290	1 400	4 780	602	1 250	1 040	1 560
1964	0.34	0.93	1.56	6.44	17.5	54.9	120	7 870	1 280	4 730	767	1 690	1 340	2 020
1965	1.25	3.60	6.86	8.95	5.97	9.58	14.6	4 200	741	3 060	723	1630	1 480	2 230
1966	6.51	18.4	28.8	38.0	23.7	34.8	46.4	1 960	366	1 720	608	1 370	1 520	2 300
1967	2.62	8.34	22.5	31.9	23.4	37.6	53.6	942	174	954	491	1 100	1 520	2 300
1968	0.91	3.29	9.30	14.1	12.1	22.0	35.6	570	89.3	578	394	875	1 520	2 290
1969	1.30	5.93	28.9	43.8	36.5	62.4	97.1	553	64.3	450	323	700	1 510	2 280
1970	1.60	5.91	21.4	33.1	28.6	51.1	81.9	650	57.0	444	274	568	1 500	2 270
1971	0.84	2.92	17.0	29.2	27.5	50.6	81.9	708	51.4	453	238	463	1 500	2 270
1972	3.53	10.3	20.3	26.9	19.0	30.4	45.2	538	35.5	366	202	374	1 480	2 250
1973	0.52	2.08	7.24	10.1	7.26	11.7	17.5	294	19.9	229	164	296	1 460	2 210
1974	3.34	9.59	18.5	24.7	17.9	29.5	45.1	285	20.6	198	137	239	1 430	2 180
1975	0.00	0.02	1.54	3.33	3.89	8.01	13.8	225	17.2	159	113	194	1 410	2 150
1976	3.63	10.1	13.6	16.3	9.29	12.8	16.2	128	9.59	102	91.0	153	1 380	2 110
1977	0.86	3.61	22.7	35.8	31.3	54.0	84.5	316	20.8	176	81.7	129	1 360	2 080
1978	0.51	1.27	1.73	3.84	3.51	7.00	10.9	305	21.9	185	74.7	112	1 340	2 060
1979	0.17	0.67	0.81	2.06	1.41	2.21	1.79	165	12.7	121	62.6	91.8	1 320	2 020
1980	4.00	11.2	14.8	16.2	8.84	11.8	15.8	84.6	6.41	70.8	50.3	72.9	1 290	1 980
1981	0.029	0.70	11.2	17.7	15.3	25.9	40.3	150	4.92	89.7	44.0	58.3	1 270	1 950
1982	-	-	0.0046	0.0280	0.102	0.34	0.15	61.5	2.19	45.4	34.1	45.3	1 240	1 910
1983	-	-	-	-	0.0007	0.0045	0.0005	25.3	0.97	23.0	26.5	35.1	1 210	1 870
1984	-	-	-	-	-	-	-	10.4	0.43	11.6	20.5	27.3	1 190	1 830
1985	-	-	-	-	-	-	-	4.28	0.19	5.88	15.9	21.2	1 160	1 790
1986	-	-	-	-	-	-	-	1.76	0.086	2.98	12.4	16.5	1 130	1 750

Table 11 (continued)

Year	Cumulative deposition density (Bq m^{-2}) [a]													
	^{131}I	^{140}Ba	^{141}Ce	^{103}Ru	^{89}Sr	^{91}Y	^{95}Zr	^{144}Ce	^{54}Mn	^{106}Ru	^{125}Sb	^{55}Fe	^{90}Sr	^{137}Cs
World (continued)														
1987	-	-	-	-	-	-	-	0.72	0.038	1.51	9.58	12.8	1 100	1 710
1988	-	-	-	-	-	-	-	0.30	0.017	0.76	7.44	9.92	1 080	1 670
1989	-	-	-	-	-	-	-	0.120	0.0076	0.39	5.77	7.70	1 050	1 630
1990	-	-	-	-	-	-	-	0.050	0.0034	0.20	4.48	5.98	1 030	1 590
1991	-	-	-	-	-	-	-	0.021	0.0015	0.10	3.47	4.65	1 000	1 560
1992	-	-	-	-	-	-	-	0.0085	0.0007	0.050	2.69	3.61	978	1 520
1993	-	-	-	-	-	-	-	0.0035	0.0003	0.025	2.09	2.80	954	1 490
1994	-	-	-	-	-	-	-	0.0014	0.0001	0.013	1.62	2.18	932	1 450
1995	-	-	-	-	-	-	-	0.0006	0.0001	0.0065	1.26	1.69	909	1 420
1996	-	-	-	-	-	-	-	-	-	0.0033	0.98	1.31	887	1 390
1997	-	-	-	-	-	-	-	-	-	0.0017	0.76	1.02	866	1 360
1998	-	-	-	-	-	-	-	-	-	0.0008	0.59	0.79	845	1 330
1999	-	-	-	-	-	-	-	-	-	0.0004	0.46	0.61	825	1 300
Total [c]														
1945-1999	482	1 440	2 900	4 380	3 220	5 220	7 130	45 400	5 920	30 300	7 420	13 200	48 440	74 100
2000-2099										0.0007	1.8	2.1	31 000	50 700
2100-2199													2 750	5 090
2200-∞													268	569
1945-∞	482	1 440	2 900	4 380	3 220	5 220	7 130	45 400	5 920	30 300	7 420	13200	83 000	131 000

a Derived from estimated fission/fusion yields of tests with atmospheric model. Includes residual deposition from previous years. Measured results used preferentially for ^{90}Sr and ^{137}Cs during 1958-1985. Latitudinal values may be derived by use of parameters in Table 8. The results for the world are the population-weighted averages of the northern and southern hemispheres (89% and 11% of the world population, respectively).

b Indicates estimated value less than 0.0001 Bq m^{-2}.

c Integrated deposition density with units Bq a m^{-2}.

Table 12
Coefficients for evaluating annual effective doses from radionuclides produced in atmospheric nuclear testing

Radionuclide	*Dose coefficient (nSv a^{-1} per Bq m^{-2})*		
	External [a]	*Ingestion* [b]	*Inhalation* [c]
^{131}I	3.28	133	0.17
^{140}Ba	18.5 [d]	0.357	0.014
^{141}Ce	0.376	–	0.034
^{103}Ru	2.72	–	0.033
^{89}Sr	–	0.601	0.16
^{91}Y	–	–	0.18
^{95}Zr	11.3 [d]	–	0.104
^{144}Ce	0.175 [d]	–	1.30
^{54}Mn	3.26	–	0.022
^{106}Ru	0.809 [d]	–	1.70
^{125}Sb	1.64	–	0.045
^{55}Fe	–	0.506	0.0043
^{90}Sr	–	– [e]	4.60
^{137}Cs	2.24	– [e]	0.11
^{238}Pu	–	–	800
^{239}Pu	–	–	840
^{240}Pu	–	–	840
^{241}Pu	–	–	12
^{241}Am	–	–	920

a Values from Beck [B2], converted with 0.869 rad R^{-1}, 0.01 Gy rad^{-1}, 0.7 Sv Gy^{-1} and applying a shielding/occupancy factor of 0.36. Relaxation length of 0.1 cm assumed for ^{131}I and ^{140}Ba, 1 cm for ^{141}Ce, ^{103}Ru and ^{95}Zr; 3 cm for remainder.

b Transfer coefficient P_{25} [U3 (page 127)] divided by the mean life of the radionuclide ($T_{½}$ divided by ln 2) applied to the average cumulative deposition.

c Transfer coefficient P_{25} [U3 (page 127)] applied to the annual deposition density (nSv per Bq m^{-2}). The exposure occurs only in the year of deposition.

d Includes decay product.

e Time–dependent model used for components of annual dose.

Table 13
External exposure to radionuclides produced in atmospheric nuclear testing

Year	*Worldwide average annual effective dose (μSv)*										
	^{131}I	$^{140}Ba,La$	^{141}Ce	^{103}Ru	$^{95}Zr,Nb$	$^{144}Ce,Pr$	^{54}Mn	$^{106}Ru,Rh$	^{125}Sb	^{137}Cs	*Total*
1945	0.0051	0.081	0.0025	0.02	0.10	0.0014	-	0.0030	0.0004	0.0007	0.22
1946	0.0034	0.055	0.0018	0.02	0.10	0.0034	-	0.0082	0.0014	0.0029	0.20
1947	- [a]	-	0.0001	-	0.020	0.0026	-	0.0075	0.0017	0.0041	0.037
1948	0.0057	0.091	0.0017	0.03	0.082	0.0025	-	0.0095	0.0021	0.0055	0.23
1949	0.0012	0.020	0.0003	0.01	0.021	0.0019	-	0.0085	0.0023	0.0068	0.068
1950	-	0.0001	-	-	0.0074	0.0011	-	0.0056	0.0020	0.0071	0.025
1951	0.036	0.56	0.012	0.15	0.52	0.0089	0.0014	0.028	0.0053	0.014	1.34
1952	0.033	0.50	0.014	0.14	0.69	0.020	0.0038	0.056	0.011	0.027	1.48
1953	0.027	0.51	0.024	0.29	1.58	0.057	0.059	0.18	0.034	0.078	2.84
1954	0.053	1.08	0.041	0.65	2.67	0.10	0.11	0.39	0.079	0.19	5.36
1955	0.025	0.39	0.009	0.14	1.00	0.16	0.15	0.72	0.17	0.45	3.21
1956	0.11	1.89	0.052	0.71	2.89	0.17	0.20	0.75	0.23	0.68	7.67
1957	0.12	1.87	0.068	0.64	4.01	0.21	0.31	0.80	0.26	0.86	9.16
1958	0.37	6.09	0.18	2.19	10.1	0.37	0.53	1.15	0.35	1.14	22.4
1959	0.012	0.29	0.046	0.62	6.32	0.55	0.86	1.64	0.48	1.65	12.5
1960	0.0038	0.061	0.0012	0.02	0.32	0.33	0.58	1.15	0.46	1.86	4.79
1961	0.15	2.33	0.067	0.55	2.32	0.18	0.32	0.70	0.39	1.96	8.97
1962	0.50	8.23	0.33	3.03	19.0	0.63	1.83	1.54	0.51	2.46	38.1
1963	0.030	0.85	0.15	1.75	20.2	1.63	4.54	3.86	0.99	3.49	37.5
1964	0.0011	0.017	0.0006	0.018	1.37	1.38	4.17	3.82	1.27	4.53	16.6
1965	0.0041	0.07	0.0026	0.024	0.17	0.74	2.41	2.47	1.19	4.98	12.1
1966	0.021	0.34	0.011	0.10	0.53	0.34	1.19	1.39	1.00	5.15	10.1
1967	0.0086	0.16	0.0084	0.087	0.61	0.16	0.56	0.77	0.81	5.16	8.34
1968	0.0030	0.06	0.0035	0.038	0.41	0.10	0.29	0.47	0.65	5.13	7.15
1969	0.0043	0.11	0.011	0.12	1.11	0.10	0.21	0.36	0.53	5.11	7.66
1970	0.0053	0.11	0.0081	0.090	0.93	0.11	0.19	0.36	0.45	5.09	7.35
1971	0.0028	0.054	0.0064	0.080	0.93	0.12	0.17	0.37	0.39	5.08	7.21
1972	0.012	0.19	0.0076	0.073	0.51	0.094	0.12	0.30	0.33	5.04	6.68
1973	0.0017	0.039	0.0027	0.027	0.20	0.051	0.065	0.18	0.27	4.96	5.80
1974	0.011	0.18	0.0069	0.067	0.51	0.050	0.067	0.16	0.23	4.89	6.17
1975	-	0.0003	0.0006	0.009	0.16	0.039	0.056	0.13	0.19	4.83	5.40
1976	0.012	0.19	0.0051	0.045	0.18	0.022	0.031	0.08	0.15	4.73	5.45
1977	0.0028	0.067	0.0085	0.098	0.96	0.055	0.068	0.14	0.13	4.65	6.19
1978	0.0017	0.024	0.0006	0.010	0.12	0.053	0.071	0.15	0.12	4.60	5.16
1979	0.0006	0.012	0.0003	0.006	0.020	0.029	0.041	0.10	0.10	4.53	4.84

Table 13 (continued)

Year	*Worldwide average annual effective dose (μSv)*										
	^{131}I	*$^{140}Ba,La$*	*^{141}Ce*	*^{103}Ru*	*$^{95}Zr,Nb$*	*$^{144}Ce,Pr$*	*^{54}Mn*	*$^{106}Ru,Rh$*	*^{125}Sb*	*^{137}Cs*	*Total*
1980	0.013	0.21	0.0056	0.044	0.18	0.015	0.021	0.057	0.083	4.44	5.07
1981	0.0001	0.013	0.0042	0.048	0.46	0.026	0.016	0.072	0.073	4.36	5.07
1982	-	-	-	-	0.0017	0.011	0.0071	0.037	0.056	4.27	4.39
1983	-	-	-	-	-	0.0044	0.0032	0.019	0.044	4.18	4.25
1984	-	-	-	-	-	0.0018	0.0014	0.0094	0.034	4.09	4.14
1985	-	-	-	-	-	0.0007	0.0006	0.0048	0.026	4.00	4.03
1986	-	-	-	-	-	0.0003	0.0003	0.0024	0.020	3.91	3.93
1987	-	-	-	-	-	0.0001	0.0001	0.0012	0.016	3.82	3.84
1988	-	-	-	-	-	0.0001	0.0001	0.0006	0.012	3.73	3.75
1989	-	-	-	-	-	-	-	0.0003	0.0095	3.65	3.66
1990	-	-	-	-	-	-	-	0.0002	0.0074	3.57	3.57
1991	-	-	-	-	-	-	-	0.0001	0.0057	3.49	3.49
1992	-	-	-	-	-	-	-	-	0.0044	3.41	3.41
1993	-	-	-	-	-	-	-	-	0.0034	3.33	3.33
1994	-	-	-	-	-	-	-	-	0.0027	3.25	3.26
1995	-	-	-	-	-	-	-	-	0.0021	3.18	3.18
1996	-	-	-	-	-	-	-	-	0.0016	3.11	3.11
1997	-	-	-	-	-	-	-	-	0.0012	3.04	3.04
1998	-	-	-	-	-	-	-	-	0.0010	2.97	2.97
1999	-	-	-	-	-	-	-	-	0.0008	2.90	2.90
1945-1999	1.58	26.7	1.09	12.0	81.3	7.94	19.2	24.5	12.2	166	353
2000-2099									0.003	114	114
2100-2199										11.4	11.4
2200-∞										1.3	1.3
1945-∞	1.58	26.7	1.09	12.0	81.3	7.94	19.2	24.5	12.2	292	479

a Estimated value less than 0.0001 μSv.

Table 14
Ingestion exposure to radionuclides produced in atmospheric nuclear testing

Year	*Worldwide average annual effective dose (μSv)*									
	^{131}I	$^{140}Ba,La$	^{89}Sr	^{55}Fe	^{90}Sr	^{137}Cs	*Total*	^{3}H	^{14}C	*Total*
1945	0.21	0.0016	0.0032	-	0.0044	0.027	0.24	0	0	0
1946	0.14	0.0011	0.0028	-	0.0088	0.040	0.19	0	0	0
1947	- [a]	-	0.0004	-	0.0059	0.016	0.022	0	0	0
1948	0.23	0.0017	0.0042	-	0.0082	0.032	0.28	0	0	0
1949	0.051	0.0004	0.0009	-	0.010	0.031	0.093	0	0	0
1950	-	-	0.0003	-	0.0060	0.0063	0.013	0	0	0
1951	1.45	0.011	0.021	0.0001	0.034	0.18	1.69	-	-	-
1952	1.33	0.010	0.019	0.0003	0.072	0.32	1.75	-	0.06	0.06
1953	1.11	0.010	0.05	0.0052	0.18	0.92	2.28	0.2	0.1	0.3
1954	2.16	0.021	0.10	0.012	0.53	2.69	5.53	0.7	0.3	1.0
1955	1.03	0.0075	0.028	0.022	1.02	4.69	6.80	0.2	0.6	0.8
1956	4.59	0.036	0.10	0.033	1.32	5.25	11.3	0.7	0.8	1.5
1957	4.69	0.036	0.10	0.049	1.46	5.10	11.4	0.6	1.1	1.7
1958	14.8	0.12	0.32	0.079	1.77	6.06	23.2	0.8	1.6	2.4
1959	0.49	0.0056	0.13	0.13	2.50	9.15	12.4	0.8	1.9	2.7
1960	0.16	0.0012	0.0048	0.13	2.45	6.53	9.27	0.4	2.0	2.4
1961	5.89	0.045	0.067	0.12	1.94	3.62	11.7	0.7	2.9	3.6
1962	20.4	0.16	0.45	0.25	3.11	10.3	34.6	7.2	5.5	12.7
1963	1.21	0.016	0.36	0.63	5.58	21.9	29.7	2.7	7.4	10.1
1964	0.046	0.0003	0.010	0.86	6.56	21.8	29.3	1.6	7.7	9.3
1965	0.17	0.0013	0.0036	0.82	5.47	12.7	19.2	1.2	7.5	8.7
1966	0.87	0.0066	0.014	0.69	4.45	6.29	12.3	1.0	7.1	8.1
1967	0.35	0.0030	0.014	0.56	3.83	3.32	8.07	0.8	6.6	7.4
1968	0.12	0.0012	0.0072	0.44	3.57	2.71	6.85	0.6	6.1	6.7
1969	0.17	0.0021	0.022	0.35	3.42	2.57	6.54	0.6	5.5	6.1
1970	0.21	0.0021	0.017	0.29	3.30	2.70	6.51	0.4	5.0	5.4
1971	0.11	0.0010	0.017	0.23	3.22	2.86	6.44	0.4	4.6	5.0
1972	0.47	0.0037	0.011	0.19	3.00	2.17	5.85	0.3	4.3	4.6
1973	0.069	0.0007	0.0044	0.15	2.72	1.33	4.28	0.3	4.0	4.3
1974	0.44	0.0034	0.011	0.12	2.60	1.55	4.73	0.2	3.8	4.0
1975	-	-	0.0023	0.10	2.50	1.57	4.18	0.2	3.5	3.7
1976	0.48	0.0036	0.0056	0.077	2.30	1.10	3.97	0.1	3.3	3.4
1977	0.11	0.0013	0.019	0.065	2.19	1.25	3.64	0.2	3.1	3.3
1978	0.068	0.0005	0.0021	0.057	2.15	1.57	3.85	0.1	2.9	3.0
1979	0.023	0.0002	0.0009	0.046	2.02	1.25	3.33	0.09	2.6	2.7

Table 14 (continued)

Year	*Worldwide average annual effective dose (μSv)*									
	^{131}I	$^{140}Ba,La$	^{89}Sr	^{55}Fe	^{90}Sr	^{137}Cs	*Total*	^{3}H	^{14}C	*Total*
1980	0.53	0.0040	0.0053	0.037	1.85	0.92	3.35	0.08	2.5	2.6
1981	0.0038	0.0002	0.0092	0.029	1.77	0.98	2.79	0.07	2.5	2.6
1982	-	-	-	-	1.66	0.85	2.51	0.06	2.4	2.5
1983	-	-	-	-	1.53	0.67	2.20	0.05	2.4	2.5
1984	-	-	-	-	1.44	0.63	2.07	0.04	2.3	2.3
1985	-	-	-	-	1.35	0.57	1.92	0.04	2.3	2.3
1986	-	-	-	-	1.26	0.52	1.78	0.03	2.2	2.2
1987	-	-	-	-	1.18	0.50	1.68	0.03	2.2	2.2
1988	-	-	-	-	1.11	0.48	1.59	0.03	2.2	2.2
1989	-	-	-	-	1.04	0.47	1.51	0.02	2.1	2.1
1990	-	-	-	-	0.98	0.45	1.43	0.02	2.1	2.1
1991	-	-	-	-	0.92	0.44	1.36	0.02	2.0	2.0
1992	-	-	-	-	0.86	0.43	1.29	0.02	2.0	2.0
1993	-	-	-	-	0.81	0.41	1.22	0.02	1.9	1.9
1994	-	-	-	-	0.76	0.40	1.16	0.01	1.9	1.9
1995	-	-	-	-	0.71	0.39	1.10	0.01	1.9	1.9
1996	-	-	-	-	0.67	0.38	1.05	0.01	1.8	1.8
1997	-	-	-	-	0.63	0.37	1.00	0.01	1.8	1.8
1998	-	-	-	-	0.59	0.36	0.95	0.009	1.7	1.7
1999	-	-	-	-	0.56	0.35	0.90	0.009	1.7	1.7
1945-1999	64.2	0.51	1.9	6.6	97.0	154	324	23.7	144	167
2000-2099					8.6	10	19	0.10	120	120
2100-2199					0.02	0.50	0.52		50	50
2200-∞					-	0.03	0.03		2 180	2 180
1945-∞	64.2	0.51	1.9	6.6	106	165	344	23.8	2 494	2 517

a Indicates estimated value less than 0.0001 μSv.

Table 15
Inhalation exposure to radionuclides produced in atmospheric nuclear testing

Year	*Worldwide average annual effective dose (μSv)*															
	^{131}I	^{140}Ba	^{141}Ce	^{103}Ru	^{89}Sr	^{91}Y	^{95}Zr	^{144}Ce	^{54}Mn	^{106}Ru	^{125}Sb	^{55}Fe	^{90}Sr	^{137}Cs	*Pu, Am*	*Total*
1945	0.0083	0.0012	0.0019	0.0021	0.0052	0.0076	0.0001	0.038	-	0.022	-	-	0.0033	0.0001	0.014	0.10
1946	0.0059	0.0009	0.0012	0.0015	0.0036	0.0053	0.0052	0.025	-	0.016	-	-	0.0024	0.0001	0.010	0.078
1947	- [a]	-	-	-	-	-	0.0034	0.0003	-	0.0002	-	-	-	-	0.0002	0.006
1948	0.0096	0.0014	0.0012	0.0024	0.0059	0.0086	-	0.024	-	0.026	-	-	0.0038	0.0001	0.016	0.097
1949	0.0020	0.0003	0.0003	0.0005	0.0013	0.0018	0.0033	0.0050	-	0.0054	-	-	0.0008	-	0.003	0.026
1950	-	-	-	-	-	-	0.0007	0.0002	-	0.0002	-	-	-	-	0.0002	0.002
1951	0.058	0.0085	0.011	0.015	0.036	0.052	-	0.20	-	0.15	0.0003	-	0.022	0.0008	0.090	0.63
1952	0.055	0.0083	0.013	0.015	0.036	0.052	0.029	0.24	0.0002	0.15	0.0003	-	0.023	0.0008	0.092	0.72
1953	0.042	0.0065	0.012	0.017	0.048	0.077	0.034	0.56	0.0005	0.52	0.0010	0.0001	0.097	0.0035	0.40	1.81
1954	0.087	0.016	0.030	0.053	0.15	0.23	0.048	1.28	0.0011	1.33	0.0026	0.0001	0.26	0.0092	1.05	4.51
1955	0.042	0.0063	0.0087	0.012	0.032	0.052	0.11	1.06	0.0008	1.30	0.0034	0.0001	0.38	0.014	1.55	4.61
1956	0.19	0.028	0.037	0.059	0.15	0.23	0.034	1.45	0.0020	1.28	0.0031	0.0002	0.35	0.013	1.43	5.21
1957	0.20	0.030	0.056	0.058	0.15	0.23	0.14	1.98	0.0024	1.36	0.0031	0.0003	0.35	0.013	1.43	6.00
1958	0.60	0.092	0.14	0.19	0.45	0.72	0.17	4.35	0.0054	2.99	0.0058	0.0005	0.46	0.017	1.89	12.0
1959	0.0002	0.0003	0.0096	0.015	0.062	0.12	0.42	3.11	0.0048	2.13	0.0049	0.0006	0.75	0.027	3.09	9.91
1960	0.0063	0.0009	0.0008	0.0016	0.0041	0.0063	0.097	0.54	0.0009	0.47	0.0016	0.0002	0.20	0.0070	0.81	2.15
1961	0.24	0.037	0.072	0.073	0.18	0.27	0.0029	1.60	0.0017	0.92	0.0020	0.0002	0.26	0.0093	1.06	4.65
1962	0.84	0.13	0.26	0.27	0.71	1.10	0.27	9.93	0.028	5.63	0.011	0.0029	1.04	0.037	4.24	24.3
1963	0.025	0.0062	0.053	0.074	0.29	0.53	0.80	15.3	0.037	9.31	0.021	0.0047	1.87	0.067	7.66	36.2
1964	0.0018	0.0003	0.0003	0.0006	0.0028	0.0075	0.47	4.29	0.012	3.17	0.011	0.0025	1.20	0.043	4.90	14.2
1965	0.0067	0.0010	0.0018	0.0018	0.0044	0.0064	0.0080	0.88	0.0026	0.79	0.0040	0.0009	0.57	0.020	2.34	4.63
1966	0.037	0.0054	0.0085	0.0094	0.023	0.035	0.0088	0.33	0.0006	0.27	0.0015	0.0003	0.25	0.0088	1.01	1.98
1967	0.013	0.0022	0.0054	0.0061	0.017	0.027	0.0237	0.26	0.0003	0.17	0.0007	0.0001	0.13	0.0045	0.52	1.18
1968	0.0036	0.0008	0.0024	0.0030	0.0093	0.016	0.025	0.36	0.0004	0.23	0.0007	0.0001	0.15	0.0052	0.59	1.39
1969	0.0069	0.0017	0.0084	0.010	0.032	0.054	0.0086	0.81	0.0010	0.48	0.0011	0.0001	0.11	0.0041	0.47	1.99
1970	0.0086	0.0017	0.0059	0.0074	0.024	0.041	0.052	0.84	0.0008	0.52	0.0013	0.0001	0.15	0.0055	0.63	2.29
1971	0.0046	0.0008	0.0033	0.0048	0.017	0.032	0.031	0.81	0.0008	0.51	0.0013	0.0001	0.14	0.0051	0.59	2.15
1972	0.019	0.0028	0.0051	0.0052	0.013	0.020	0.023	0.31	0.0002	0.21	0.0006	-	0.067	0.0024	0.28	0.95
1973	0.0028	0.0006	0.0021	0.0026	0.0075	0.012	0.017	0.15	0.0002	0.10	0.0003	-	0.025	0.0009	0.10	0.43
1974	0.018	0.0027	0.0050	0.0053	0.015	0.023	0.013	0.36	0.0004	0.22	0.0005	0.0001	0.088	0.0031	0.36	1.11
1975	-	-	0.0001	0.0002	0.0008	0.002	0.014	0.12	0.0001	0.08	0.0002	-	0.043	0.0016	0.18	0.44
1976	0.021	0.0031	0.0055	0.0057	0.014	0.020	0.0013	0.12	0.0001	0.075	0.0002	-	0.021	0.0007	0.084	0.37
1977	0.004	0.0008	0.0044	0.0058	0.020	0.036	0.015	0.66	0.0008	0.38	0.0008	0.0001	0.059	0.0021	0.24	1.43
1978	0.0033	0.0005	0.0004	0.0007	0.0018	0.0028	0.030	0.17	0.0002	0.13	0.0004	-	0.072	0.0026	0.29	0.71
1979	0.0003	0.0001	0.0001	0.0002	0.0006	0.0009	0.0014	0.035	-	0.031	0.0001	-	0.023	0.0008	0.094	0.19
1980	0.022	0.0033	0.0060	0.0060	0.015	0.021	0.0004	0.12	-	0.067	0.0001	-	0.022	0.0008	0.090	0.37
1981	-	-	0.0008	0.0012	0.005	0.009	0.016	0.17	0.0001	0.102	0.0002	-	0.032	0.0011	0.13	0.48
1982	-	-	-	-	-	-	-	0.016	-	0.012	-	-	0.0094	0.0003	0.038	0.048
1983	-	-	-	-	-	-	-	0.0020	-	0.0018	-	-	0.0066	0.0002	0.027	0.034
1984	-	-	-	-	-	-	-	0.0003	-	0.0271	-	-	0.0053	0.0002	0.022	0.027
1985	-	-	-		-	-	-	-	-	0.0001	-	-	0.0016	0.0001	0.0065	0.008
Total	2.58	0.40	0.77	0.93	2.56	4.07	2.92	52.5	0.11	35.2	0.085	0.014	9.22	0.33	37.8	149

a Estimated value less than 0.0001 μSv.

Table 16
Annual effective dose from radionuclides produced in atmospheric nuclear testing

Year	*Average annual effective dose (μSv)*											
	Northern hemisphere				*Southern hemisphere*				*World*			
	External	*Ingestion* [a]	*Inhalation*	*Total*	*External*	*Ingestion* [a]	*Inhalation*	*Total*	*External*	*Ingestion* [a]	*Inhalation*	*Total*
1945	0.25	0.27	0.12	0.64	- [b]	-	-	-	0.22	0.24	0.10	0.57
1946	0.22	0.21	0.087	0.52	-	-	-	-	0.20	0.19	0.077	0.47
1947	0.042	0.025	0.0046	0.071	-	-	-	-	0.037	0.02	0.0041	0.06
1948	0.26	0.31	0.11	0.68	-	-	-	-	0.23	0.28	0.10	0.60
1949	0.077	0.10	0.027	0.21	-	-	-	-	0.068	0.09	0.024	0.19
1950	0.028	0.014	0.0016	0.043	-	-	-	-	0.025	0.01	0.0014	0.039
1951	1.50	1.90	0.72	4.12	0.0016	0.0010	0.0014	0.0039	1.34	1.69	0.64	3.67
1952	1.65	2.02	0.80	4.48	0.082	0.15	0.032	0.27	1.48	1.81	0.72	4.01
1953	3.17	2.92	2.01	8.10	0.14	0.34	0.17	0.65	2.84	2.58	1.81	7.23
1954	5.88	7.17	4.95	18.0	1.14	1.35	1.28	3.77	5.36	6.53	4.55	16.4
1955	3.52	8.26	5.03	16.8	0.66	1.89	0.79	3.34	3.21	7.60	4.57	15.4
1956	8.40	14.0	5.76	28.2	1.83	3.03	1.15	6.01	7.67	12.8	5.26	25.8
1957	9.38	13.5	6.40	29.3	7.38	9.47	2.72	19.6	9.16	13.1	6.00	28.3
1958	24.2	27.7	13.2	65.2	7.82	8.15	2.99	19.0	22.4	25.6	12.1	60.1
1959	13.6	16.6	10.8	41.0	2.98	4.17	1.16	8.31	12.5	15.1	9.75	37.3
1960	5.26	12.6	2.30	20.2	0.97	3.45	0.76	5.18	4.79	11.7	2.13	18.6
1961	9.98	16.7	5.23	31.9	0.83	3.79	0.65	5.26	8.97	15.3	4.73	29.0
1962	39.6	50.0	26.5	116	25.3	25.5	8.16	59.0	38.1	47.3	24.5	110
1963	41.3	43.7	40.2	125	6.62	7.36	2.73	16.7	37.5	39.8	36.0	113
1964	18.3	42.3	15.6	76.2	2.14	8.32	2.02	12.5	16.6	38.6	14.1	69.3
1965	13.3	30.4	5.04	48.7	1.78	8.53	1.38	11.7	12.1	27.9	4.63	44.6
1966	10.9	21.8	2.07	34.8	3.25	9.11	1.24	13.6	10.1	20.4	1.98	32.5
1967	9.01	16.7	1.23	26.9	2.93	5.68	0.76	9.37	8.34	15.5	1.18	25.0
1968	7.66	14.6	1.42	23.7	3.03	4.84	1.15	9.02	7.15	13.6	1.39	22.1
1969	8.25	13.6	2.11	24.0	2.93	4.49	1.09	8.52	7.66	12.6	1.99	22.3
1970	7.77	12.7	2.38	22.9	3.88	5.62	1.53	11.0	7.35	11.9	2.28	21.5
1971	7.63	12.2	2.25	22.1	3.78	5.08	1.31	10.2	7.21	11.4	2.15	20.8
1972	7.21	11.2	1.00	19.4	2.39	4.21	0.59	7.19	6.68	10.4	0.96	18.1
1973	6.24	9.17	0.43	15.8	2.23	3.54	0.36	6.14	5.80	8.58	0.42	14.8
1974	6.53	9.27	1.16	17.0	3.22	4.08	0.69	7.98	6.17	8.73	1.11	16.0
1975	5.82	8.51	0.46	14.8	2.06	2.72	0.24	5.01	5.40	7.88	0.44	13.7
1976	5.95	7.97	0.41	14.3	1.43	2.47	0.093	4.00	5.45	7.37	0.37	13.2
1977	6.79	7.43	1.59	15.8	1.36	2.33	0.091	3.78	6.19	6.94	1.43	14.6
1978	5.64	7.39	0.79	13.8	1.32	2.20	0.072	3.59	5.16	6.85	0.71	12.7
1979	5.28	6.56	0.21	12.0	1.27	2.03	0.040	3.34	4.84	6.02	0.19	11.1
1980	5.54	6.46	0.41	12.4	1.24	1.92	0.036	3.20	5.07	5.93	0.37	11.4
1981	5.55	5.77	0.52	11.8	1.21	1.87	0.030	3.11	5.07	5.36	0.47	10.9
1982	4.78	5.41	0.083	10.3	1.18	1.81	0.022	3.01	4.39	4.97	0.076	9.43

Table 16 (continued)

Year	*Average annual effective dose (μSv)*											
	Northern hemisphere				*Southern hemisphere*				*World*			
	External	*Ingestion* [a]	*Inhalation*	*Total*	*External*	*Ingestion* [a]	*Inhalation*	*Total*	*External*	*Ingestion* [a]	*Inhalation*	*Total*
1983	4.64	5.01	0.040	9.69	1.15	1.77	0.018	2.93	4.03	4.65	0.038	8.94
1984	4.51	4.79	0.060	9.36	1.12	1.72	0.010	2.85	3.93	4.41	0.055	8.60
1985	4.40	4.57	0.0087	8.98	1.10	1.68	0.005	2.78	3.84	4.26	0.008	8.30
1986	4.29	4.36	0.0006	8.65	1.07	1.64	0.0003	2.71	3.75	4.01	0.0006	7.94
1987	4.18	4.19	0.0003	8.38	1.05	1.62	0.0002	2.66	3.66	3.91	0.0002	7.75
1988	4.08	4.04	-	8.12	1.02	1.61	-	2.63	3.57	3.82	-	7.57
1989	3.99	3.90	-	7.89	1.00	1.60	-	2.60	3.49	3.63	-	7.29
1990	3.90	3.76	-	7.65	0.97	1.60	-	2.58	3.41	3.55	-	7.12
1991	3.81	3.63	-	7.43	0.95	1.61	-	2.56	3.33	3.38	-	6.87
1992	3.72	3.50	-	7.22	0.93	1.62	-	2.55	3.26	3.31	-	6.72
1993	3.63	3.37	-	7.01	0.91	1.63	-	2.54	3.18	3.14	-	6.48
1994	3.55	3.26	-	6.81	0.89	1.65	-	2.54	3.11	3.07	-	6.33
1995	3.47	3.14	-	6.61	0.87	1.68	-	2.55	3.04	3.01	-	6.20
1996	3.39	3.03	-	6.42	0.85	1.72	-	2.57	2.97	2.86	-	5.97
1997	3.31	2.92	-	6.23	0.83	1.76	-	2.59	2.90	2.81	-	5.85
1998	3.24	2.81	-	6.05	0.81	1.82	-	2.63		2.66	-	5.63
1999	3.16	2.71	-	5.87	0.79	1.89	-	2.68		2.61	-	5.51
1945-1999	382	531	164	1 076	115	178	35	328	353	492	149	994
2000-2099	124	141		264	31	126		157	114	139		253
2100-2199	12	51		63	3.1	50		53	11	51		62
2200-∞	1.4	2 180		2 181	0.3	2 180		2 180	1.3	2 180		2 181
1945-∞	520	2 900	164	3 580	149	2 530	35	2 720	479	2 860	149	3 490

a Includes contribution from globally dispersed ^{3}H and ^{14}C.
b Estimated value less than 0.0001 μSv.

Table 17
Local doses from atmospheric nuclear testing

Test site	*Population*	*Maximum absorbed dose in thyroid of children (Gy)*	*Maximum effective dose (Sv)*	*Collective effective dose (man Sv)*	*Ref.*
United States					
Nevada	180 000	1		500 [b]	[A1]
Pacific [a]	245	200	1.9	160	[L4]
Former USSR					
Semipalatinsk	10 000 [c]	20		4 600	[T1]
United Kingdom					
Australian sites [d]				700	[W1]

a Exposures from Bravo test of 28 February 1954 to residents of Rongelap, Utrik, and Ailinginae atolls.
b External exposure to local population only.
c Population in settlements bordering the test site. The extended population of Semipalatinsk and Altai regions was 1.7 million in 1960.
d Maralinga, Emu, and Monte Bello Island.

Table 18
Distribution of cumulative effective doses to individuals exposed in local areas downwind of the Nevada test site
[A1]

Effective dose (mSv)		*Number of individuals*		*Collective effective dose (man Sv)*	
Range	*Mean [a]*	*1951–1958*	*1961–1963*	*1951–1958*	*1961–1963*
<0.06–0.6	0.2	61 000	180 000	12	36
0.6–3	1.3	80 000	480	104	0.6
3–6	4.2	19 000	0	80	
6–30	13	20 000	0	260	
30–60	42	520	0	22	
60–90	73	45	0	3.2	
Total (rounded)		180 000	180 000	460	40

a Assumed to be geometric mean of range.

Table 19
Estimated local exposures from atmospheric nuclear tests conducted by France at the South Pacific test site
[B8]

Location	*Date of test*	*Population*	*Effective dose (mSv)*				*Collective effective dose (man Sv)*
			External	*Inhalation*	*Ingestion*	*Total*	
Gambier Islands	2 July 1966 8 August 1971	40 68	3.4 0.9	0.18 0.002	1.9 0.24	5.5 1.2	0.2 0.5
Tureia Atoll	2 July 1967 12 June 1971	516 545	0.7 0.9	0.023 0.003	0.17 0.043	0.9 1.3	0.7 0.08
Tahiti (Mahina)	17 July 1974	84,000	0.6	0.08	0.06	0.8	67
Total							70

Table 20
Effective dose estimates from external exposures at locations 400–800 km downwind of the Lop Nor test site
[Z1]

City	*Population*	*Distance from test site (km)*	*Absorbed dose in air (mGy)*	*Effective dose (mSv)*
Xihu)			0.07	0.2
Anxi)	60 000	500	0.06	0.2
Tashi)		500	0.10	0.3
Qiaowan	(Village)	560	0.14	0.04
Yumenzhen)	159 000	600	0.12	0.03
Yumanshi)			0.02	0.006
Jinta	99 000	740	0.45	0.11
Jiayuguan	89 000	720	0.44	0.11

Table 21
Underground nuclear tests [a]

Year	*Number of tests*						
	China	*France*	*India*	*Pakistan*	*United Kingdom*	*United States*	*USSR*
1955						1	
1957						5	
1958						14	
1961		1				10	1
1962		1			2	57	1
1963		3				45	
1964		3			2	48	9
1965		4			1	39	15
1966		1				49	19
1967						42	23
1968						72	23
1969	1					61	24
1970						60	21
1971						28	29
1972						32	31
1973						27	22
1974			1		1	25	27
1975	1	2				23	35
1976	1	5			1	20	27
1977		9				23	36
1978	1	11			2	20	55
1979		10			1	15	52
1980		12			3	14	43
1981		12			1	16	37
1982	1	10			1	18	34
1983	2	9			1	19	37
1984	2	8			2	18	52
1985		8			1	17	10
1986		8			1	14	
1987	1	8			1	16	39
1988	1	8				18	29
1989		9			1	15	11
1990	2	6			1	10	8
1991		6			1	9	
1992	2					8	
1993	1						
1994	2						
1995	2	5					
1996	2	1					
1997							
1998			5	6			
Total	22	160	6	6	24	908	750
All countries	1 876						

a Includes cratering tests carried out by the United States and the USSR, some of which released radionuclides to the atmosphere.

Table 22
Summary of nuclear testing

Country	*Number of tests*			*Yield (Mt)*		
	Atmospheric	*Underground*	*Total*	*Atmospheric*	*Underground*	*Total*
China	22	22	44	20.7	1	22
France	50 [a]	160	210	10.2	3	13
India	–	6	6			
Pakistan	–	6	6			
United Kingdom	33 [b]	24	57	8.1	2	10
United States	219 [c]	908	1 127	154	46	200
USSR	219	750	969	247	38	285
All countries	543	1 876	2 419	440	90	530

a Includes 5 safety tests.
b Includes 12 safety tests.
c Includes 22 safety tests and 2 combat explosions.

Table 23
Radionuclide releases and estimated local exposures from nuclear weapons material production and fabrication plants in the United States

Location	*Release period*	*Airborne release (GBq)*	*Liquid release (GBq)*	*Cumulative effective dose (mSv)*		*Reference*
				Airborne	*Liquid*	
Fernald	1954–1980	50–150 (U)				[S5]
Oak Ridge	1942–1984	~1 000 000 (^{131}I)	25 400 (^{137}Cs)			[H9, W5]
Rocky Flats	1953–1983 (routine) 1957 (fire) 1965–1969 (storage area)	8.8 (U) / 1.7 (Pu) 1.9 (Pu) 260 (Pu)		0.0015 0.013 0.072		[R3] [M4] [M5]
Hanford	1944–1987	27 300 000 (^{131}I)	481 000 000 (^{24}Na)	12	15	[H4, S3]
Savannah River	1954–1989	140 (Pu)	23 (Pu)	0.12	0.0024	[C1]

Table 24
Releases of radioactive materials associated with the early operation of the materials production complex at Chelyabinsk-40 in the eastern Urals region of the Russian Federation
[D5, K4, N8]

Circumstances of release	*Time period*	*Radionuclide composition (%)*					*Total activity release (PBq)*
		^{90}Sr	*^{95}Zr*	*^{106}Ru*	*^{137}Cs*	*^{144}Ce*	
Routine operation Atmospheric effluents Liquid effluents to Techa River [a]	 1948–1956 1949–1956	 11.6	 13.6	 25.9	 12.2	 	 100
Accident at waste storage site	1957	5.4	24.9	3.7	0.036	66.0	74
Resuspension from shoreline of Lake Karachay	1967	34			48	18	0.022

a Radionuclide composition included, additionally, ^{89}Sr (8.8%) and other (27.9%).

Table 25
Estimated collective effective dose from operation of weapons material production centres in the former Soviet Union [D5, K4, K5, N8]

Production centre	*Time period*	*Population exposed*	*Collective effective dose (man Sv)*
Chelyabinsk			
Discharges to Techa River	1949–1956	28 000	6 200
Waste storage accident	1957	273 000	2 500
Krasnoyarsk			
Discharges to Yenesei River	1958–1991	200 000	1 200
Tomsk			
Discharges to Tom/Ob Rivers	1958–1992	400 000	200
Total			10 100

Table 26
Present (1990–1993) levels of contamination surrounding the Chelyabinsk site [K4]

Location	*Material*	*Deposition density (kBq m^{-2})*		*Concentration (Bq kg^{-1})*	
		^{90}Sr	*^{137}Cs*	*^{90}Sr*	*^{137}Cs*
Techa River	Water			7–23	0.06–0.23
	Bottom sediments			40–2 000 [a]	100–280 000 [a]
	Fish			50–560	4–10
Eastern Urals					
Agricultural areas	Soil	3.7–74	7.4–37		
	Potatoes			0.2–6.7	0.5–3.8
	Grain			0.5–12.6	0.3–2.9
	Milk			0.2–6.3	0.2–4.5
	Beef			0.2–1.7	0.3–2.6
Forest areas	Soil	37–74 000	37–740		
	Mushrooms			400–1 100	110–1 600
	Berries			700–16 000	150
Lakes removed from use	Water			17–120	0.7
	Bottom sediments				250–860 [a]
	Fish			70 000–110 000	1 700
Lakes of multipurpose use	Water			0.10–0.34	0.06–0.36
	Bottom sediments			20–300 [a]	80–240 [a]
	Fish			30–220	8–26

a Dry weight.

Table 27
Present (1993–1996) exposures from nuclear materials production/processing centres in the Russian Federation [B7, K4]

Installation	*Population*	*Annual effective dose (mSv)*			*Annual collective effective dose (man Sv)*
		External	*Internal*	*Total*	
Chelyabinsk	320 000	0.01	0.10	0.11	35
Krasnoyarsk	200 000	0.03	0.02	0.05	10
Tomsk	400 000	0.0004	0.005	0.0054	2.2

Table 28
Production of uranium
[O1]

Country	*Annual production of uranium (t)* [a]							
	1990	*1991*	*1992*	*1993*	*1994*	*1995*	*1996*	*1997*
Argentina	9	18	123	126	80	65	28	35
Australia	3 530	3 776	2 334	2 256	2 208	3 712	4 974	5 520
Belgium [b]	39	38	36	34	40	25	28	27
Brazil	5	0	0	24	106	106	0	0
Bulgaria	405	240	150	100	70	0	0	0
Canada	8 729	8 160	9 297	9 155	9 647	10 473	11 788	12 029
China	(800)	(800)	(955)	(780)	(780)	(500)	(500)	(500)
Czech Republic	2 142	1 778	1 539	950	541	600	598	590
France	2 841	2 477	2 149	1 730	1 053	1 016	940	748
Gabon	709	678	589	556	650	652	560	472
Germany	2 972	1 207	232	116	47	35	40	40
Hungary	524	415	430	380	413	210	200	200
India	(230)	(200)	150	148	155	(155)	(200)	(200)
Kazakhstan	(7 120)	(7 350)	(2 802)	2 700	2 240	1 630	1 320	1 000
Mongolia	89	101	105	54	72	20	0	0
Namibia	3 211	2 450	1 660	1 679	1 895	2 016	2 452	2 905
Niger	2 839	2 963	2 965	2 914	2 975	2 974	3 160	3 497
Pakistan	(30)	(30)	(23)	(23)	(23)	(23)	(23)	(23)
Portugal	111	28	28	32	24	18	15	17
Romania	210	160	120	(120)	120	120	100	100
Russian Federation	3 780	3 050	2 640	2 697	2 541	2 160	2 000	(2 000)
Slovenia	53	0	2 [c]	0	0	0	0	0
South Africa	2 460	1 712	1 669	1 699	1 671	1 421	1 436	1 100
Spain	213	196	187	184	256	255	255	255
Ukraine	(1 000)	(1 000)	1 000	1 000	1 000	1 000	500	500
United States	3 420	3 060	2 170	1 180	1 279	2 324	2 420	2 170
Uzbekistan	(2 100)	2 100	2 680	2 600	2 015	1 644	1 459	2 000
Total	49 571	43 987	36 035	33 237	31 611	33 154	34 996	35 692

a Values in parentheses are estimates.
b Uranium is produced as a byproduct from imported phosphates.
c Decommissioning product.

Table 29
Radon releases in airborne effluents and collective dose from uranium mining and milling

Source	*Release per unit production (GBq t^{-1})*	*Release rate per unit area (Bq s^{-1} m^{-2})*	*Normalized release* [a] *[TBq $(GWa)^{-1}$]*	*Normalized collective effective dose [man Sv $(GWa)^{-1}$]* [b]
Mining	300		75	0.19
Milling	13		3	0.0075
Mill tailings				
Operational mill		10	3 [c]	0.04 [d]
Closed mill		1	0.3 [c]	7.5 [e]

a Normalization basis: production, 250 t $(GW\ a)^{-1}$; tailings, 1 ha $(GWa)^{-1}$.
b Dose coefficient: 0.0025 man Sv TBq^{-1}.
c Normalized release rate: TBq a^{-1} $(GWa)^{-1}$.
d Assuming release period of five years.
e Assuming release period of 10,000 years and unchanging population density.

Table 30
Worldwide installed capacity and electrical energy generated by nuclear reactors
[I3]

Country	*Capacity (GW)*	*Electrical energy generated (GW a)*							
		1990	*1991*	*1992*	*1993*	*1994*	*1995*	*1996*	*1997*
PWRs									
Armenia									
Armenia 1-2	0.376	0	0	0	0	0	0	0.239	0.163
Belgium									
Doel 1-4	2.71	2.191	2.284	2.296	2.080	1.923	2.221	2.235	2.478
Tihange 1-3	2.791	2.442	2.359	2.413	2.468	2.489	2.266	2.472	2.643
Brazil									
Angra 1	0.626	0.235	0.149	0.172	0.046	0.005	0.266	0.261	0.341
Bulgaria									
Kozloduy 1-6	3.538	1.542	1.387	1.213	1.417	1.612	1.852	1.919	1.877
China									
Guangdong 1-2	1.812	-	-	-	-	1.331	1.149	1.316	1.416
Qinshan	0.288	-	-	-	0.199	0.188	0.236	0.237	0.230
Maanshan 1-2	1.78	1.397	1.446	1.369	1.462	1.522	1.468	1.585	1.411
Czech Republic									
Dukovany 1-4	1.632	1.343	1.272	1.398	1.441	1.481	1.396	1.375	1.426
Finland									
Loviisa 1-2	0.89	0.743	0.776	0.751	0.798	0.756	0.736	0.779	0.868
France									
Belleville 1-2	2.62	1.625	1.888	1.913	1.917	1.691	1.792	1.666	2.088
Blayais 1-4	3.64	2.541	2.688	2.556	2.582	2.315	2.841	3.081	2.977
Bugey 2-5	3.64	2.076	1.908	1.380	2.355	2.306	2.415	2.367	2.548
Cattenom 1-4	5.2	1.994	2.385	3.718	3.579	3.624	3.713	4.078	4.038
Chinon B1-B4	3.55	2.585	2.494	2.825	2.598	2.573	2.884	2.789	2.842
Chooz-A (Ardennes)	0.305	0.169	0.152	0	0	0	0	0	0
Chooz B1-B2	-	-	-	-	-	-	-	-	0.998
Cruas 1-4	3.555	2.663	2.350	2.490	2.579	2.547	2.547	2.802	2.485
Dampierre 1-4	3.56	2.078	2.486	2.461	2.700	2.345	2.513	2.666	2.486
Fessenheim 1-2	1.76	0.980	1.069	0.807	1.293	1.311	1.250	1.411	1.328
Flamanville 1-2	2.66	1.702	1.581	1.878	1.973	1.773	1.898	2.053	1.758
Golfech 1-2	2.62	0.208	1.089	0.807	1.154	1.717	1.704	2.041	2.032
Gravelines 1-6	5.46	3.995	3.918	3.943	3.976	4.012	4.245	4.070	4.020
Nogent 1-2	2.62	1.615	1.735	1.841	1.929	1.687	1.701	1.907	1.997
Paluel 1-4	5.32	3.334	3.563	3.195	3.786	3.276	3.742	3.398	3.814
Penly 1-2	2.66	0.330	0.963	1.492	1.899	1.910	1.946	2.202	1.892
St. Alban 1-2	2.67	1.583	1.815	1.277	1.576	1.678	1.859	1.880	1.731
St. Laurent B1-B2	1.795	1.288	1.147	1.268	1.223	1.418	1.114	1.324	1.266
Tricastin 1-4	3.66	2.554	2.381	2.673	2.698	2.703	2.784	2.991	2.677
Germany									
Biblis A-B	2.386	1.616	1.238	1.657	1.790	1.765	1.183	1.355	1.880
Brokdorf	1.326	0.952	1.084	1.232	1.078	1.168	1.132	1.205	1.284
Emsland	1.242	1.146	1.060	1.160	1.196	1.202	1.198	1.205	1.216
Grafenrheinfeld	1.235	0.903	1.113	1.102	1.010	1.104	1.135	1.088	1.157
Greifswald	1.632	0	0	0	0	0	0	0	0
Grohnde	1.3	1.156	1.137	1.190	1.219	1.172	1.230	1.209	1.354
Isar 2	1.31	1.058	1.107	1.124	1.164	1.199	1.146	1.172	1.245
Mülheim-Kärlich	1.219	0	0	0	0	0	0	0	0
Neckarwestheim 1-2	2.02	1.763	1.694	1.767	1.766	1.898	1.883	1.903	1.866
Obrigheim	0.34	0.135	0.120	0.215	0.299	0.300	0.247	0.317	0.316
Philippsburg 2	1.268	0.972	1.131	1.073	1.196	1.174	1.204	1.281	1.269
Stade	0.64	0.480	0.262	0.485	0.514	0.611	0.498	0.575	0.565
Unterweser	1.23	0.969	0.740	0.997	1.236	0.877	0.911	1.131	1.134
Hungary									
Paks 1-4	1.84	1.472	1.473	1.594	1.575	1.510	1.507	1.531	1.501

Table 30 (continued)

Country	*Capacity (GW)*	*Electrical energy generated (GW a)*							
		1990	*1991*	*1992*	*1993*	*1994*	*1995*	*1996*	*1997*
Japan									
Genkai 1-4	2.185	0.843	0.809	0.771	0.964	1.751	1.746	1.759	2.420
Ikata 1-3	1.922	0.952	0.904	0.815	0.809	1.198	1.691	1.460	1.648
Mihama 1-3	1.57	1.356	0.807	0.655	0.707	0.934	0.768	1.195	1.318
Ohi 1-4	4.49	1.385	1.671	2.780	3.614	3.379	2.855	3.845	3.346
Sendai 1-2	1.692	1.406	1.285	1.491	1.420	1.295	1.306	1.432	1.503
Takahama 1-4	3.22	2.277	2.140	2.462	2.520	2.341	2.552	2.415	2.631
Tomari 1-2	1.10	0.514	0.778	0.832	0.987	0.961	0.926	0.877	0.982
Tsuruga 2	1.115	0.822	1.057	0.924	0.895	0.892	1.053	0.921	0.745
Netherlands									
Borssele	0.481	0.329	0.311	0.323	0.380	0.379	0.387	0.402	0.248
Republic of Korea									
Kori 1-4	2.951	2.388	2.415	2.457	2.500	2.502	2.563	2.623	2.458
Ulchin 1-2	1.84	1.337	1.588	1.604	1.622	1.572	1.708	1.686	1.582
Yonggwang 1-4	3.7	1.468	1.530	1.522	1.559	1.754	2.389	3.185	3.298
Russian Federation									
Balakovo 1-4	3.8	1.362	1.674	2.038	1.730	1.565	1.428	1.936	1.763
Kalinin 1-2	1.9	1.368	1.280	1.402	1.232	1.016	1.195	1.030	1.036
Kola 1-4	1.644	1.317	1.279	1.139	1.085	0.774	0.982	0.938	0.933
Novovoronezh 2-5	1.72	1.033	1.064	1.049	1.183	0.793	0.940	1.015	1.234
Slovakia									
Bohunice 1-4	1.632	1.274	1.240	1.261	1.163	1.280	1.296	1.286	1.233
Slovenia									
Krsko	0.62	0.501	0.539	0.430	0.430	0.503	0.522	0.498	0.547
South Africa									
Koeberg 1-2	1.844	0.966	1.047	1.062	0.835	1.106	1.289	1.342	1.441
Spain									
Almaraz 1-2	1.86	1.611	1.625	1.515	1.626	1.579	1.530	1.504	1.448
Asco 1-2	1.86	1.549	1.556	1.593	1.542	1.583	1.448	1.596	1.636
José Cabrera 1	0.16	0.109	0.120	0.128	0.104	0.002	0.040	0.112	0.093
Trillo 1	1.07	0.727	0.740	0.906	0.844	0.905	0.853	0.871	0.886
Vandellos 2	1.00	0.837	0.820	0.767	0.789	0.823	0.864	0.857	0.827
Sweden									
Ringhals 2-4	2.63	1.987	2.177	1.969	1.790	2.211	1.966	2.153	2.184
Switzerland									
Beznau 1-2	0.7	0.593	0.584	0.554	0.549	0.656	0.618	0.629	0.662
Gösgen	0.94	0.814	0.815	0.846	0.846	0.875	0.893	0.905	0.910
Ukraine									
Khmelnitski 1	0.95	0.742	0.590	0.694	0.626	0.720	0.651	0.513	0.702
Rovno 1-3	1.695	1.341	1.197	1.501	1.237	1.238	1.180	1.229	1.317
South Ukraine 1-3	2.85	1.556	1.808	2.034	1.886	1.671	1.806	1.814	2.173
Zaporozhe 1-6	4.75	2.680	2.933	3.500	2.944	2.614	2.645	3.712	3.884
United Kingdom									
Sizewell B	1.188	-	-	-	-	-	0.614	0.966	0.959
United States									
Arkansas One 1-2	1.694	1.287	1.446	1.294	1.538	1.589	1.333	1.524	1.622
Beaver Valley 1-2	1.643	1.194	1.196	1.364	1.093	1.430	1.312	1.197	1.163
Braidwood 1-2	2.24	1.669	1.320	1.816	1.833	1.602	1.843	1.784	1.864
Byron 1-2	2.21	1.485	1.723	1.825	1.711	1.861	1.814	1.678	1.857
Callaway 1	1.118	0.914	1.139	0.924	0.958	1.142	0.942	1.015	1.022
Calvert Cliffs 1-2	1.65	0.153	1.039	1.222	1.405	1.286	1.477	1.381	1.500
Catawba 1-2	2.258	1.530	1.593	1.864	1.801	1.994	1.904	1.778	2.030
Comanche Peak 1-2	2.3	0.287	0.612	0.792	1.288	1.670	1.937	1.727	2.002
Crystal River 3	0.821	0.473	0.623	0.607	0.694	0.678	0.826	0.276	0
Davis-Besse 1	0.86	0.475	0.667	0.873	0.694	0.729	0.876	0.737	0.820
Diablo Canyon 1-2	2.16	1.860	1.722	1.907	1.921	1.743	1.858	1.909	1.950
Donald Cook 1-2	2.08	1.269	1.772	0.733	1.862	1.061	1.598	1.872	1.190

Table 30 (continued)

Country	*Capacity (GW)*	*Electrical energy generated (GW a)*							
		1990	*1991*	*1992*	*1993*	*1994*	*1995*	*1996*	*1997*
United States *(continued)*									
Farley 1-2	1.654	1.391	1.388	1.265	1.384	1.508	1.238	1.471	1.451
Fort Calhoun 1	0.478	0.276	0.371	0.290	0.354	0.470	0.384	0.357	0.436
R. E. Ginna	0.47	0.394	0.398	0.398	0.399	0.385	0.415	0.331	0.445
Haddam Neck	0.565	0.136	0.423	0.444	0.427	0.434	0.418	0.317	0
Harris 1	0.86	0.724	0.677	0.620	0.859	0.692	0.681	0.807	0.675
Indian Point 1-3	1.829	1.171	1.276	1.443	0.813	0.872	0.727	1.564	0.858
Kewaunee	0.503	0.445	0.420	0.450	0.436	0.452	0.433	0.362	0.270
Maine Yankee	0.81	0.555	0.715	0.612	0.655	0.757	0.023	0.578	0
McGuire 1-2	2.258	1.284	1.868	1.629	1.411	1.774	2.049	1.806	1.559
Millstone 2-3	2.005	1.544	0.779	1.064	1.461	1.495	1.225	0.402	0
North Anna 1-2	1.83	1.508	1.519	1.334	1.360	1.631	1.583	1.492	1.711
Oconee 1-2-3	2.538	2.300	2.174	2.017	2.301	2.044	2.261	1.764	1.567
Palisades	0.73	0.343	0.556	0.555	0.405	0.515	0.532	0.607	0.662
Palo Verde 1-3	3.663	2.351	2.865	2.923	2.515	2.645	3.080	3.293	3.369
Point Beach 1-2	0.97	0.836	0.835	0.830	0.873	0.874	0.819	0.794	0.192
Prairie Island 1-2	1.003	0.871	0.967	0.767	0.927	0.944	0.969	0.939	0.818
Rancho Seco 1	0.873	0.004	0	0	0	0	0	0	0
H. B. Robinson 2	0.665	0.379	0.547	0.464	0.479	0.531	0.575	0.623	0.707
Salem 1-2	2.212	1.307	1.652	1.148	1.307	1.300	0.528	0	0.293
San Onofre 1-3	2.586	1.881	1.882	2.118	1.688	2.107	1.598	1.985	1.541
Seabrook 1	1.15	0.467	0.778	0.898	1.033	0.708	0.957	1.124	0.907
Sequoyah 1-2	2.296	1.601	1.894	1.790	0.386	1.365	1.794	1.938	1.946
South Texas 1-2	2.5	1.430	1.656	2.010	0.155	1.626	2.195	2.361	2.266
St. Lucie 1-2	1.678	1.124	1.509	1.435	1.160	1.346	1.235	1.393	1.395
Surry 1-2	1.562	1.211	1.207	1.330	1.230	1.272	1.286	1.509	1.380
Three Mile Island 1	0.808	0.607	0.647	0.792	0.681	0.752	0.729	0.811	0.676
Trojan	1.095	0.697	0.171	0.526	0	0	0	0	0
Turkey Point 3-4	1.332	0.887	0.244	0.921	1.188	1.115	1.256	1.246	1.221
Virgil C. Summer 1	0.885	0.698	0.610	0.858	0.697	0.509	0.863	0.817	0.830
Vogtle 1-2	2.166	1.623	1.872	1.959	1.973	2.072	2.186	1.962	2.121
Waterford 3	1.075	0.982	0.830	0.870	1.043	0.905	0.886	1.019	0.767
Watts Bar	1.170	-	-	-	-	-	-	0.633	0.868
Wolf Creek	1.135	0.901	0.673	0.969	0.903	0.976	1.149	0.940	0.964
Yankee NPS	0.167	0.094	0.113	0	0	0	0	0	0
Zion 1-2	2.08	0.810	1.072	1.082	1.406	1.176	1.415	1.477	0.123
BWRs									
China									
Chin Shan 1-2	1.208	0.731	0.933	0.930	0.954	0.870	0.918	0.921	1.063
Kuosheng 1-2	1.902	1.472	1.488	1.407	1.349	1.430	1.472	1.641	1.526
Finland									
Olkiluoto 1-2	1.465	1.325	1.325	1.323	1.348	1.337	1.333	1.353	1.421
Germany									
Brunsbüttel	0.771	0.546	0.436	0.398	0	0	0.343	0.536	0.583
Gundremmingen B,C	2.488	1.907	1.866	1.912	1.679	1.864	2.061	2.155	2.080
Isar 1	0.87	0.577	0.772	0.670	0.636	0.588	0.736	0.664	0.685
Krümmel	1.26	1.008	0.883	0.950	0.749	0.283	1.052	0.941	1.056
Philippsburg 1	0.864	0.594	0.705	0.743	0.527	0.750	0.721	0.791	0.732
Würgassen	0.64	0.125	0.466	0.432	0.449	0.384	0	0	0
India									
Tarapur 1-2	0.3	0.206	0.162	0.181	0.199	0.128	0.198	0.087	0.201
Japan									
Fukushima Daiichi 1-6	4.546	2.780	3.383	3.028	2.453	3.248	3.837	3.321	3.295
Fukushima Daini 1-4	4.268	2.562	3.202	3.239	2.933	3.076	3.572	3.528	3.593
Hamaoka 1-4	3.469	1.652	1.624	1.552	2.610	2.258	3.161	2.847	2.878
Kashiwazaki Kariwa 1-7	7.965	2.201	2.599	2.622	3.405	3.969	4.552	5.151	6.613
Onagawa 1-2	1.294	0.325	0.382	0.470	0.263	0.391	0.849	1.016	1.169
Shika 1	0.505	-	-	-	0.324	0.378	0.399	0.394	0.506
Shimane 1-2	1.23	1.012	0.988	0.932	1.062	0.970	0.953	0.291	1.122
Tokai 2	1.056	0.832	0.802	0.718	0.994	0.836	0.781	0.861	1.014
Tsuruga 1	0.341	0.224	0.258	0.227	0.300	0.172	0.266	0.286	0.221

Table 30 (continued)

Country	*Capacity (GW)*	*Electrical energy generated (GW a)*							
		1990	*1991*	*1992*	*1993*	*1994*	*1995*	*1996*	*1997*
Mexico									
Laguna Verde 1-2	1.30	0.232	0.464	0.428	0.539	0.464	0.860	0.858	1.144
Netherlands									
Dodewaard	0.05	0.047	0.047	0.048	0.049	0.048	0.045	0.045	0.008
Spain									
Confrentes	0.99	0.807	0.799	0.880	0.801	0.798	0.935	0.878	0.787
S. Maria de Garona	0.46	0.291	0.420	0.305	0.419	0.358	0.437	0.366	0.384
Sweden									
Barsebeck 1-2	1.2	0.974	1.040	0.629	0.682	0.946	0.899	0.903	0.871
Forsmark 1-3	3.008	2.355	2.661	2.484	2.534	2.774	2.674	2.680	2.466
Oskarshamn 1-3	2.207	1.619	1.871	1.473	1.250	1.477	1.484	1.673	1.862
Ringhals 1	0.75	0.517	0.644	0.386	0.456	0.615	0.647	0.741	0.255
Switzerland									
Leibstadt	0.99	0.867	0.806	0.860	0.838	0.798	0.876	0.880	0.886
Mühleberg	0.322	0.283	0.276	0.276	0.293	0.302	0.305	0.302	0.291
United States									
Big Rock Point	0.067	0.049	0.056	0.031	0.049	0.047	0.059	0.042	0.022
Browns Ferry 1-3	3.195	0.012	0.434	0.958	0.659	0.838	1.137	1.923	1.929
Brunswick 1-2	1.58	0.960	0.921	0.364	0.457	1.231	1.369	1.244	1.474
Clinton 1	0.946	0.411	0.690	0.563	0.671	0.846	0.697	0.606	0
Cooper	0.764	0.583	0.548	0.711	0.424	0.254	0.471	0.724	0.623
Dresden 2-3	1.545	1.058	0.636	0.829	0.916	0.657	0.613	0.585	1.099
Duane Arnold-1	0.538	0.345	0.473	0.392	0.370	0.469	0.427	0.450	0.474
Enrico Fermi 2	1.093	0.813	0.706	0.840	0.946	0	0.586	0.547	0.637
Fitzpatrick	0.757	0.525	0.385	0	0.542	0.568	0.548	0.604	0.756
Grand Gulf 1	1.142	0.845	1.041	0.933	0.902	1.098	0.892	1.053	1.235
Hatch 1-2	1.525	1.214	1.100	1.239	1.137	1.231	1.315	1.455	1.375
Hope Creek 1	1.031	0.465	0.845	0.806	1.007	0.813	0.807	0.773	0.733
Lasalle 1-2	2.072	1.696	1.776	1.400	1.492	1.527	1.615	1.021	0
Limerick 1-2	1.055	1.469	1.744	1.681	1.851	1.876	1.889	1.957	2.002
Millstone 1	0.654	0.582	0.203	0.413	0.602	0.376	0.497	0	0
Monticello	0.536	0.514	0.411	0.508	0.441	0.452	0.543	0.442	0.418
Nine Mile Point 1-2	1.682	0.623	1.191	0.922	1.318	1.515	1.299	1.527	1.322
Oyster Creek	0.62	0.491	0.337	0.517	0.533	0.415	0.593	0.495	0.579
Peach Bottom 2-3	2.086	1.625	1.169	1.468	1.600	1.863	1.888	1.950	1.956
Perry 1	1.141	0.758	1.025	0.818	0.454	0.524	1.040	0.854	0.931
Pilgrim 1	0.67	0.484	0.391	0.541	0.496	0.437	0.512	0.608	0.492
Quad Cities 1-2	1.538	1.109	1.009	0.871	0.931	0.649	0.957	0.839	0.935
River Bend 1	0.936	0.638	0.763	0.315	0.600	0.558	0.905	0.783	0.779
Susquehanna 1-2	2.07	1.682	1.811	1.551	1.549	1.749	1.784	1.927	1.920
Vermont Yankee	0.504	0.413	0.469	0.426	0.385	0.493	0.440	0.434	0.487
WPPSS 2	1.095	0.661	0.488	0.651	0.815	0.771	0.793	0.635	0.700
HWRs									
Argentina									
Atucha 1	0.335	0.197	0.311	0.255	0.274	0.303	0.305	0.233	0.311
Embalse	0.600	0.571	0.514	0.497	0.545	0.589	0.445	0.558	0.541
Canada									
Bruce 1-4	3.394	1.623	2.163	1.889	1.132	1.612	1.665	1.478	0.973
Bruce 5-8	3.371	2.759	3.019	2.699	2.277	2.742	2.648	2.857	2.704
Darlington 1-4	3.524	0.132	0.251	0.258	2.502	3.042	3.153	2.962	2.118
Gentilly-2	0.64	0.466	0.448	0.562	0.588	0.617	0.516	0.598	0.481
Pickering 1-4	2.06	0.804	1.143	1.264	1.650	1.475	0.858	0.746	1.142
Pickering 5-8	2.064	1.584	1.838	1.522	1.669	1.732	1.705	1.026	1.211
Point Lepreau	0.635	0.609	0.621	0.551	0.607	0.598	0.184	0.524	0.394
India									
Kakrapar 1-2	0.202	-	-	-		0.015	0.219	0.299	0.228
Kalpakkam 1-2	0.44	0.222	0.181	0.200	0.170	0.210	0.155	0.192	0.211
Narora 1-2	0.44	-	0.051	0.150	0.048	0.087	0.226	0.273	0.360
Rajasthan 1-2	0.414	0.176	0.125	0.106	0.151	0.060	0	0	0.030
Japan									
Fugen	0.165	0.099	0.128	0.109	0.119	0.110	0.143	0.115	0.077

Table 30 (continued)

Country	*Capacity (GW)*	*Electrical energy generated (GW a)*							
		1990	*1991*	*1992*	*1993*	*1994*	*1995*	*1996*	*1997*
Pakistan									
Karachi	0.125	0.043	0.042	0.057	0.042	0.060	0.053	0.035	0.044
Republic of Korea									
Wolsong 1	0.629	0.545	0.578	0.553	0.641	0.523	0.530	0.513	1.026
Romania									
Cernavoda 1	0.650	-	-	-	-	-		0.135	0.565
United Kingdom									
Winfrith	0.092	0.042	0	0	0	0	0	0	0
GCRs									
France									
Bugey 1	0.54	0.229	0.155	0.131	0.179	0.166	0	0	0
Chinon A2-3	0.54	0.143	0	0	0	0	0	0	0
St. Laurent A1-2	0.84	0.100	0.282	0.152	0	0	0	0	0
Japan									
Tokai 1	0.159	0.103	0.102	0.120	0.021	0.072	0.095	0.134	0.109
Spain									
Vandellos 1	0.48	0	0	0	0	0	0	0	
United Kingdom									
Berkeley	0.138	0	0	0	0	0	0	0	0
Bradwell	0.245	0.169	0.184	0.135	0.187	0.207	0.176	0.173	0.136
Calder Hall	0.198	0.157	0.155	0.162	0.168	0.170	0.163	0.159	0.157
Chapelcross	0.192	0.163	0.155	0.165	0.174	0.177	0.176	0.178	
Dungeness A	0.424	0.342	0.365	0.428	0.368	0.404	0.382	0.313	0.405
Dungeness B1-B2	0.72	0.169	0.471	0.390	0.662	0.566	0.170	0.689	0.606
Hartlepool A1-A2	0.84	0.564	0.549	0.825	0.995	0.913	0.828	1.008	0.967
Heysham 1A-B, 2A-B	2.07	0.811	1.183	1.586	1.924	1.928	1.803	1.883	1.989
Hinkley Point A	0.47	0.303	0.326	0.242	0.391	0.372	0.403	0.307	0.394
Hinkley Point B, A-B	1.25	0.864	0.794	0.858	0.980	1.025	1.062	0.905	0.993
Hunterston A1	0.3	0	0	0	0	0	0	0	0
Hunterston B1-B2	1.15	0.910	0.772	0.718	0.828	0.968	0.970	0.333	0.977
Oldbury A	0.434	0.333	0.363	0.390	0.404	0.398	0.389	0.381	0.402
Sizewell A	0.42	0.307	0.314	0.259	0.345	0.385	0.321	0.045	0.199
Torness A-B	1.25	0.444	0.590	0.944	0.872	0.891	0.994	0.314	1.045
Trawsfynydd	0.39	0.302	0.037	0	0	0	0	0	0
Wylfa	0.84	0.770	0.851	0.890	0.824	0.698	0.764	0.813	0.858
LWGRs									
Lithuania									
Ignalina 1-2	2.76	1.792	1.782	1.671	1.260	0.757	1.214	1.446	1.239
Russian Federation									
Bilibino 1-4	0.044	0.034	0.029	0.032	0.024	0.021	0.014	0.015	0.014
Kursk 1-4	3.7	2.605	2.401	2.120	2.334	1.852	1.857	2.001	1.930
Leningrad 1-4	3.7	2.431	2.395	2.092	2.329	2.111	1.888	2.075	2.409
Smolensk 1-3	1.85	1.999	2.175	2.334	2.228	1.711	1.762	2.088	1.738
Ukraine									
Chernobyl 1-3	2.575	1.815	1.509	0.602	1.327	1.089	1.228	1.210	0.463
FBRs									
France									
Creys-Malville	1.2	0.067	0	0	0	0.001		0.387	
Phenix	0.233	0.112	0	0	0.004	0.003		0.0003	
Kazakhstan									
Bn-350	0.135	-	-	0.053	0.051	0.043	0.009	0.010	0.035
Russian Federation									
Beloyarsky 3	0.56	0.365	0.387	0.467	0.447	0.435	0.390	0.425	0.405

Table 30 (continued)

Country	*Capacity (GW)*	*Electrical energy generated (GW a)*							
		1990	*1991*	*1992*	*1993*	*1994*	*1995*	*1996*	*1997*
United Kingdom									
Dounreay PFR	0.25	0.061	0.089	0	0.103	0.038	0	0	0
All reactors									
All countries									
PWRS	224.1	138.7	145.3	151.8	152.9	157.1	161.7	169.4	167.7
BWRs	72.9	48.0	51.9	49.2	51.2	52.8	60.0	59.6	61.6
HWRs	19.8	9.9	11.4	10.7	12.4	13.8	12.8	12.5	12.4
GCRs	13.9	7.2	7.6	8.4	9.3	9.3	8.7	7.6	9.2
LWGRs	15.0	10.7	10.3	8.9	9.5	7.5	8.0	8.8	7.8
FBRs	2.4	0.61	0.48	0.52	0.61	0.52	0.40	0.82	0.44
Total	347.9	215.1	227.0	229.5	236.0	241.0	251.6	258.9	259.2

Table 31
Noble gases released from reactors in airborne effluents

Country / reactor	*Release (GBq)*							
	1990	*1991*	*1992*	*1993*	*1994*	*1995*	*1996*	*1997*
PWRs								
Armenia [A5]								
Armenia 2							25 600	29 000
Belgium [M1]								
Doel 1-4	15 600	31 300	26 400	5 190	972	4 120	2 050	73.8
Tihange 1-3	34 100	16 600	10 900	40 500	11 900	4 120	14 600	9 810
Brazil [C7]								
Angra 1	318	688	20 100	44 800	176	229	7 720	61 600
Bulgaria [C6]								
Kozloduy 1-6	541 000	402 000	202 000	210 000	264 000	250 000	390 000	203 000
China [C8, T2]								
Guangdong 1-2	-	-	-		22 700	80 200	43 600	31 100
Qinshan	-	-	6.4	27.5	30.7	55.2	36.6	15.1
Maanshan 1-2	770	354	148	74	166	467	866	28.4
Czech Republic [N2]								
Dukovany 1-4	1 670	10 700	11 800	18 600	20 000	48 300	31 500	5 590
Finland [F1]								
Loviisa 1-2	1 000	1 000	1 800	1 600	1 400	24 000	1 100	3 400
France [E1]								
Belleville 1-2	60 000	44 000	16 000	46 000	22 000	20 000	22 000	23 000
Blayais 1-4	179 000	149 000	29 000	53 000	67 000	57 000	17 000	16 000
Bugey 2-5	42 000	45 000	12 000	19 000	11 000	13 000	12 000	10 000
Cattenom 1-4	81 000	99 000	48 000	22 000	26 000	24 000	22 000	24 000
Chinon B1-B4	139 000	169 000	76 000	40 000	41 000	44 000	34 000	25 000
Chooz-A (Ardennes)	71 000	129 000	50 000	37 000	45 000	40 000	240	210
Chooz B1-B2	-	-	-	-	-	-	16 000	10 000
Cruas 1-4	22 000	27 000	14 000	27 000	34 000	19 000	25 000	17 000
Dampierre 1-4	179 000	75 000	34 000	38 000	56 000	34 000	18 000	19 000
Fessenheim 1-2	8 200	13 000	6 200	7 900	5 500	6 800	9 200	7 100
Flamanville 1-2	5 900	6 500	15 000	14 000	11 000	11 000	11 000	31 000
Golfech 1-2	6 400	10 000	7 700	10 000	16 000	14 000	14 000	22 000
Gravelines 1-6	60 000	43 000	57 000	36 000	20 000	24 000	25 000	21 000
Nogent 1-2	46 000	28 000	24 000	29 000	16 000	16 000	12 000	15 000
Paluel 1-4	129 000	129 000	40 000	40 000	30 000	29 000	28 000	25 000
Penly 1-2	8 600	11 000	9 400	12 000	17 000	9 900	13 000	13 000
St. Alban 1-2	10 000	15 000	13 000	13 000	12 000	12 000	10 000	13 000
St. Laurent B1-B2	4 600	1 900	8 600	9 100	9 300	18 000	10 000	11 000
Tricastin 1-4	30 000	34 000	28 000	29 000	25 000	26 000	26 000	28 000
Germany [B3]								
Biblis A-B	9 800	7 000	10 500	10 600	12 100	8 300	2 600	4 490
Brokdorf	410	720	300	180	1 000	35 000	800	3 700
Emsland	98	110	100	270	610	600	120	100
Grafenrheinfeld	4 800	51	150	0	0	0	160	0
Greifswald	360 000	0	0	0	0	0	0	0
Grohnde	140	1 100	680	930	4 600	18 000	25 000	240
Isar 2	220	240	280	330	150	220	170	170
Mülheim-Kärlich	0	0	0	0	0	0	0	0
Neckarwestheim 1-2	18 200	13 500	15 500	6 100	4 000	3 700	4 600	2 150
Obrigheim	130	50	150	1 200	430	620	330	200
Philippsburg 2	110	480	1 800	360	11 000	1 700	1 100	5 800
Stade	2 200	1 900	1 600	1 300	2 100	1 700	1 900	1 200
Unterweser	3 200	2 700	4 500	4 700	3 100	3 600	3 500	3 500
Hungary [F2]								
Paks 1-4	178 000	146 800	195 400	166 000	183 700	174 300	81 300	44 200

Table 31 (continued)

Country / reactor	*Release (GBq)*							
	1990	*1991*	*1992*	*1993*	*1994*	*1995*	*1996*	*1997*
Japan [J1, J5]								
Genkai 1-4	650	520	370	230	170	130	85	66
Ikata 1-3	4.2	28	480	7.2	0.57	1.1	0.45	0.60
Mihama 1-3	250	280	1 100	200	110	160	190	190
Ohi 1-4	680	560	530	470	600	510	430	430
Sendai 1-2	59	32	38	30	32	39	37	34
Takahama 1-4	350	1 800	440	620	200	210	330	370
Tomari 1-2	0.73	3.8	1.6	0.17	0.41	2.5	3.0	2.4
Tsuruga 2	9.6	6.5	2.9	2.7	3.6	0.38	3.8	3.0
Netherlands [N7]								
Borssele	7 860	4 300	1 130	763	27 900	6 530	1 950	6 410
Republic of Korea [K1]								
Kori 1-4	12 600	18 500	102 000	206 000	14 000	4 100	6 000	6 790
Ulchin 1-2	6 180	241	104	56.6	20.0	41.0	215	680
Yonggwang 1-4	5 770	7 290	6 590	59 20	5 000	11 000	5 500	4 220
Russian Federation [M6]								
Balakovo 1-4	40 700	26 800	62 900	60 100	15 800	13 500	6 880	6 380
Kalinin 1-2	56 700	30 300	36 700	31 900	27 000	20 300	18 400	24 700
Kola 1-4	272 000	359 900	275 500	178 300	78 800	129 600	101 300	75 600
Novovoronezh 2-5	47 400	44 400	33 500	27 000	24 300	24 300	33 800	38 000
Slovakia [N2, S4]								
Bohunice 1-4	20 100	26 600	22 200	17 700	17 600	17 800	24 400	26 400
Slovenia [S1]								
Krsko	1 630	620	2 530	5 030	9 960	24 800	12 580	2 500
South Africa [C11]								
Koeberg 1-2	14 520	16 970	25 190	44 600	45 480	67 610	132 300	12 200
Spain [C2]								
Almaraz 1-2	4 790	7 480	7 060	13 200	4 830	29 700	52 900	46 700
Asco 1-2	168 700	64 110	13 960	23 400	40 500	19 410	3 550	2 380
José Cabrera 1	45 900	34 900	50 100	56 200	4 670	31 100	21 800	15 600
Trillo 1	10 800	17.1	17.2	1 260	436	5 060	87.2	8 030
Vandellos 2	79 600	23 400	4 330	306	57.2	144	264	283
Sweden [N3]								
Ringhals 2-4	218 000	69 700	58 700	25 100	18 600	15 300	24 200	1 330
Switzerland [F3]								
Beznau 1-2	29 000	46 000	30 000	19 000	28 000	2 600	2 600	2 500
Gösgen	7 400	5 100	4 500	11 000	3 800	19 000	13 000	24 000
Ukraine [G3]								
Khmelnitski 1	56 200	32 000	74 800	21 300	14 300	57 000	74 100	21 700
Rovno 1-3	87 100	69 300	89 800	44 000	113 000	100 000	93 200	89 100
South Ukraine 1-3	51 400	52 800	78 200	98 300	32 800	48 900	70 200	50 400
Zaporozhe 1-6	101 000	154 000	200 000	122 000	117 000	122 000	80 600	112 000
United Kingdom [M7]								
Sizewell B	-	-	-	-	-	-	6 110	4 360
United States [T3]								
Arkansas One 1-2	32 900	77 100	95 900	2 590	14 400	153 000	16 650	127
Beaver Valley 1-2	3 020	5 510	5 740	20 600	7 620	5 810	10 500	5 660
Braidwood 1-2	90 300	389 000	8 620	102 000	56 100	1 100		
Byron 1-2	45 900	3 850	13 900	4 510		4 260	1 010	
Callaway 1	33 400	5 030	14 800	29 900	1 220	1 820	5 150	14 900
Calvert Cliffs 1-2	24 900	95 100	217 000	7 920	5 740	3 130	2 940	7 960
Catawba 1-2	39 500	29 700	31 700	48 000	33 400	8 810	5 330	6 310
Comanche Peak 1-2	33 500	218 000	65 100	7 100	81	1 046	932	95
Crystal River 3	270 000	52 200	29 100	1 410	4 320		386	
Davis-Besse 1	40 300	42 900	1 340	12 900	5 460	11 100	17 800	164
Diablo Canyon 1-2	2 080	1 710	91.0	79.2	7 230	16 500	6 180	82.5
Donald Cook 1-2	6 960	2 620	7 570	76 200	10 730	5 030	3 860	639

Table 31 (continued)

Country / reactor	*Release (GBq)*							
	1990	*1991*	*1992*	*1993*	*1994*	*1995*	*1996*	*1997*
United States *(continued)*								
Farley 1-2	4 480	17 200	26 200	8 140	7 780	2 690	2 530	5 210
Fort Calhoun 1	17 000	13 200	5 590	343	1 960	20 000	307 000	
R. E. Ginna	22 000	19 000	20 000	5 180	1 840	1 660	3 170	
Haddam Neck	54 000	226 000	103	77 000				
Harris 1	22 100	31 900	50 300	12 900	7 070	8 210	1 590	1 380
Indian Point 1-3	106 000	54 400	195 000	63 700				
Kewaunee	85.5	67.0	59.2	1 360	16.2	6.4	1.5	0
Maine Yankee	35 000	41 800	14 800	1 670	720	618	456	1 530
McGuire 1-2	38 400	33 200	30 000	35 800	38 300	9 320	962	292
Millstone 2-3	114 400	15 300	23 500	1 600	1 740	3 650	667	0
North Anna 1-2	35 300	8 300	45 400	9 300	1 600	1 300	700	900
Oconee 1-2-3	327 000	128 000	122 000	24 300	129 500	47 730	3 370	2 340
Palisades	4 480	2 320	2 760	3 440	656	6 180	2 140	823
Palo Verde 1-3	95 600	143 000	91 200	38 400	16 500	12 100	9 810	
Point Beach 1-2	297	740	1 870	374	359	910	271	66.2
Prairie Island 1-2	3 060	2 070	940	1 360	879	3 120	40.3	27.7
Rancho Seco 1	8.14	0	2.56	0				
H. B. Robinson 2	258	83.6	281	12 430	2 140	99.2	470	36.9
Salem 1-2	17 100	20 600	34 900	54 100	27 500	7 130	0.39	360
San Onofre 1-3	110 000	140 000	205 000	72 600	13 500	25 800	15 800	8 320
Seabrook 1	3 960	1 080	33.8	4.0				
Sequoyah 1-2	225 000	52 500	7 660	2 850	4 200		1 390	
South Texas 1-2	10 400	4 890	33 700	1 560	2 020	1 170	1 170	7 210
St. Lucie 1-2	42 700	94 000	36 600	12 800	6 310	13 900		
Surry 1-2	16 600	1 300	600	1 500	10 200	8 400	14 800	18 400
Three Mile Island 1	24 600	4 500	21 200	88 600	12 500	22 600	55.9	540
Trojan	7 620	6 140	7 660	1 980	914	415	711	325
Turkey Point 3-4	47 400	682	4 580	16 800	1 090			
Virgil C. Summer 1	27 800	16 100	12 500	8 990	5 000	103	21.9	9.4
Vogtle 1-2	6 960	13 200	4 200	8 680	2 900	41 400	67 800	8 300
Waterford 3	212 000	79 600	25 600	33 800	76 800	64 380	2 970	20 500
Watts Bar	-	-	-				7 190	
Wolf Creek	37 000	111 000	11 400	19 200			53 600	
Yankee NPS	4 250	7 970	0	0	0	0	0	0
Zion 1-2	4 070	10 200	12 400	98 200	68 600	49 100	1 710	132
BWRs								
China [T2]								
Chin Shan 1-2	26 700	33 000	99 200	26 500	7 510	11 900	2 290	1 210
Kuosheng 1-2	3 550	2 910	1 280	784	995	1 870	227	334
Finland [F1]								
Olkiluoto 1-2	22 000	43 000	29 000	9 500	41 000	52 000	18 000	1 100
Germany [B3]								
Brunsbüttel	4 800	1 300	1 600	0	0	6 600	7 200	3 900
Gundremmingen B,C	7 000	130	11	2.8	21	1.2	0	310
Isar 1	0.2	1.2	0	150	93	400	150	810
Krümmel	690	450	6 100	540	160	17 000	14 000	11 000
Philippsburg 1	14	130	1 200	340	1 800	880	520	860
Würgassen	610	2 100	1 400	1 000	960	0	21	0
India [B4]								
Tarapur 1-2	5 940 000	7 629 000	6 348 000	9 410 000	6 560 000			
Japan [J1, J5]								
Fukushima Daiichi 1-6	0	0	0	0	0	0	0	0
Fukushima Daini 1-4	0	0	0	0	0	0	0	0
Hamaoka 1-4	0	0	0	0	190	0	0	0
Kashiwazaki Kariwa 1-7	0	0	0	0	0	0	0	0
Onagawa 1-2	0	0	0	0	0	0	0	0
Shika 1	-	-	0	0	0	0	0	0
Shimane 1-2	0	0	0	0	0	0	0	0
Tokai 2	0	0	0	0	0	0	0	0
Tsuruga 1	0.55	3.9	0	0	0	0	0	0

Table 31 (continued)

Country / reactor	*Release (GBq)*							
	1990	*1991*	*1992*	*1993*	*1994*	*1995*	*1996*	*1997*
Mexico [C5]								
Laguna Verde 1-2	3 400	2 240	567	134	25	1 570	374	345
Netherlands [N7]								
Dodewaard	33 000	6 410	11 800	13 500	12 800	3 190	3 880	23 300
Spain [C2]								
Confrentes	26 700	119 000	136 000	46 100	21 400	9 320	5 150	8 000
S. Maria de Garona	53 500	73 700	58 100	73 100	17 100	7 470	648	294
Sweden [N3]								
Barsebeck 1-2	59 100	407 000	24 600	16 000	20 500	22 100	17 900	7 320
Forsmark 1-3	450 000	654 000	501 000	394 000	68 300	19 800	87 000	25 600
Oskarshamn 1-3	1 970 000	1 260 000	546 000	279 000	266 000	112 000	138 000	794 000
Ringhals 1	56 670	71 800	1 440 000	12 700 000	24 300 000	15 700 000	6 690 000	1 310 000
Switzerland [F3]								
Leibstadt	48 000	38 000	19 000	29 000	74 000	17 000	8 700	8 500
Mühleberg	110 000	16 000	3 600	3 800	2 700	2 000	2 000	2 000
United States [T3]								
Big Rock Point	205 000	167 000	66 200	190 000	246 000	181 300	129 000	81 800
Browns Ferry 1-3	0	77 700	618 000	148 000	23 800			
Brunswick 1-2	41 400	25 000	18 100	12 600	17 660	159 600	26 400	35 000
Clinton 1	356	26.2	273	309	43	5.62	4.80	0
Cooper	6 920	958	519	238	1 470	662	71 700	536 000
Dresden 2-3	755	466	488	1 790	276	3 260	2 440	8 970
Duane Arnold 1	1 690	1 220	1 750	2 110	1 970	1 820	1 490	1 790
Enrico Fermi 2	5 960	2 300	7 700	5 740	18.1	888	2 450	30 100
Fitzpatrick	50 000	75 900	6 330	15 400	14 500	3 950	23 800	2 510
Grand Gulf 1	5 030	1 170	7 840	3 490	1 240	2 170	3 460	1 440
Hatch 1-2	40 800	10 400	38 700	141 000	63 800	53 700	157 000	183 500
Hope Creek 1	30 700	7 100	5 140	2 710	16.3	5 550	960	852
Lasalle 1-2	25 400	3 920	4 370	38 600	1 540	145		
Limerick 1-2	1 270	2 630	31 700	5 960	2 910	16 900		
Millstone 1	4 330	870	165	12 200	400	13 200	0	0
Monticello	110 000	73 600	48 100	22 200	20 100	16 700	14 400	12 600
Nine Mile Point 1-2	6 030	5 570	13 800	20 000	8 580			
Oyster Creek	27 200	17 000	15 200	8 100	12 500	2 900	2 360	810
Peach Bottom 2-3	414 000	888 000	312 000	411 000	646 000	656 000	35 300	
Perry 1	3 100	4 110	12 100	25 300	8 690	19 700	4 150	
Pilgrim 1	33 600	82 300	43 400	34 900	68 600	86 600	17 800	7 160
Quad Cities 1-2	2 950	1 560	1 820	1 410	1 110	2 050	1 030	998
River Bend 1	38 100	41 400	17 200	25 800	25 000	6 150	7 510	8 460
Susquehanna 1-2	2 670	2 130	2 120	625	439	566	629	667
Vermont Yankee	188 000	112 000	219 000	140 000	117 000	329	228	127
WPPSS 2	32 900	26 800	5 590	5 220	259	888	666	
HWRs								
Argentina [C3]								
Atucha 1	89 000	11 000	3 000	110 000	240 000	360 000	320 000	960 000
Embalse	660 000	1 200 000	150 000	42 000	17 000	44 000	180 000	30 000
Canada [A2]								
Bruce 1-4	518 000	903 000	564 000	435 000	248 000	100 000	88 000	54 000
Bruce 5-8	37 000	35 000	41 000	101 000	70 300	67 000	70 000	74 000
Darlington 1-4	21 000	67 000	73 000	146 000	141 000	110 000	380 000	295 000
Gentilly 2	60 000	48 000	33 000	69 000	59 000	73 000	54 000	21 000
Pickering 1-4	407 000	500 000	326 000	370 000	344 000	310 000	310 000	290 000
Pickering 5-8	237 000	212 000	207 000	215 000	222 000	220 000	200 000	210 000
Point Lepreau	0	13 000	11 000	4 900	5 100	2 200	5 600	5 900
India [B4]								
Kakrapar 1-2	-	-	-					
Kalpakkam 1-2	18 110 000	12 790 000	13 910 000	5 539 000	11 440 000			
Narora 1-2	22 240	34 730	635 000	226 100	2 579 000			
Rajasthan 1-2	11 620 000	10 380 000	4 760 000	12 430 000	4 443 000			

Table 31 (continued)

Country / reactor	*Release (GBq)*							
	1990	*1991*	*1992*	*1993*	*1994*	*1995*	*1996*	*1997*
Japan [J1, J5]								
Fugen	0	22	0	0	0	0	0	0
Pakistan [P2]								
Karachi	0	0	0	0	0	0	0	0
Republic of Korea [K1]								
Wolsong 1-2	112 000	114 000	65 900	219 000	120 000	750 000	3 200 000	60 300
Romania								
Cernavoda 1	-	-	-	-	-	-	60 300	61 700
United Kingdom [N5]								
Wilfrith		0	3.27	7.85	2.1			0.42
GCRs								
France [E1]								
Bugey 1	77 000	53 000	11 000	15 000	9 200	3 800	-	0
Chinon A2-3	32 000	9 100	6 700	110	110	210	250	220
St. Laurent A1-2	78 000	43 000	16 000	200	140	-	-	-
Japan [J1, J4]								
Tokai 1	270 000	250 000	300 000	0	280 000	250 000	310 000	360 000
Spain [C2]								
Vandellos 1	891	432	959	334	0	0	0	
U. K. [M7, N4, N5]								
Berkeley	0	0	0	0				
Bradwell	595 000	650 000	410 000	693 000	773 000	662 000	647 000	510 000
Calder Hall	2 500 000	2 500 000	2 560 000	2 700 000	2 800 000	2 700 000		2 600 000
Chapelcross	2 900 000	3 000 000	3 000 000	3 200 000	3 200 000	3 200 000	3 210 000	2 730 000
Dungeness A	1 123 000	1 170 000	1 310 000	1 192 000	1 244 000	1 195 000	1 190 000	977 000
Dungeness B1-B2	16 800	30 000	22 000	30 000	23 000	7 000	27 900	19 300
Hartlepool A1-A2	6 600	12 900	12 500	20 200	44 000	13 000	23 900	37 800
Heysham 1A-B, 2A-B	15 300	15 600	55 200	24 000	23 000	50 000	23 600	28 900
Hinkley Point A	2 148 000	2 511 000	2 118 000	3 171 000	3 060 000	3 200 000	33 200	3 030 000
Hinkley Point B, A-B	82 000	89 000	95 000	39 000	39 000	42 000	33 200	16 700
Hunterston A1	86 000	0	0	0	0	0	0	0
Hunterston B1-B2	60 000	29 000	21 000	30 000	30 000	55 000	49 500	66 100
Oldbury A	108 000	81 000	143 000	207 000	170 000	250 000	112 000	111 000
Sizewell A	1 872 000	1 8010 00	1 676 000	2 0230 00	2 347 000	1 952 000	295 000	1 230 000
Torness A-B	5 600	5 300	3 800	5 000	8 100	7 000	6 990	12 200
Trawsfynydd	1 489 000	219 000	0	0	0	0	0	0
Wylfa	70 500	30 000	56 000	55 500	36 000	19 000	43 900	51 400
LWGRs								
Lithuania [E2]								
Ignalina 1-2	2 370 000	1 800 000	700 000	480 000	290 000	283 000	158 000	99 700
Russian Federation [M6]								
Bilibino 1-4	297 300	276 900	345 400	326 000	418 700	293 100	395 700	270 100
Kursk 1-4	8 700 000	6 030 000	6 075 000	6 285 000	3 009 000	1 113 000	1 152 000	611 700
Leningrad 1-4	1 606 000	1 539 000	1 392 000	1 614 000	1 789 000	1 073 000	1 036 000	958 900
Smolensk 1-3	7 170 000	4 473 000	3 815 000	2 257 000	1 121 000	1 022 000	675 300	686 600
Ukraine [G3]								
Chernobyl 1-3	3 730 000	3 770 000	3 200 000	3 800 000	1 700 000	900 000	610 000	91 900
FBRs								
France [E1]								
Creys-Malville	46 000	43 000	43 000	44 000	45 000	45 000	44 000	43 000
Phenix								
Kazakhstan [A6]								
Bn-350	140 000	165 000	139 000	117 000	108 000	48 300	48 400	102 000

Table 31 (continued)

Country / reactor	*Release (GBq)*							
	1990	*1991*	*1992*	*1993*	*1994*	*1995*	*1996*	*1997*
Russian Federation [M6] Beloyarsky 3	12 900	11 000	8 100	8 100	13 500	4 070	4 070	8 100
United Kingdom [N5] Dounreay PFR	12 100	18 900	0	6 050	11 100	0	0	0

Summary parameter	*Reactor*	*Release (TBq)*							
		1990	*1991*	*1992*	*1993*	*1994*	*1995*	*1996*	*1997*
All reactors									
Total release (TBq)	PWRs	5 900	4 888	3 714	3 041	2 242	2 393	2 321	1 436
	BWRs	10 090	11 990	10 730	24 280	32 680	17 220	7 499	3 112
	HWRs	31 890	26 310	20 780	19 910	19 930	2 036	4 868	2 062
	GCRs	13 540	12 500	11 820	13 410	14 090	13 610	6 006	11 780
	LWGRs	23 870	17 890	15 530	14 760	8 328	4 682	4 027	2 719
	FBRs	211	238	190	175	178	97	96	153
	All	85 500	73 810	62 760	75 570	77 440	40 040	24 820	21 260
Annual normalized release [TBq (GW a)$^{-1}$]	PWRs	43	34	25	20	15	16	14	9.5
	BWRs	210	231	218	474	619	300	141	59
	HWRs	3 250	2 310	1 950	1 600	1 450	167	413	178
	GCRs	1 880	1 630	1 410	1 440	1 510	1 560	803	1 280
	LWGRs	2 240	1 740	1 750	1 550	1 100	588	456	349
	FBRs	428	500	365	292	343	244	117	348
	All	399	327	275	321	329	166	102	93
Average normalized release 1990-1994 and 1995-1997 [TBq (GW a)$^{-1}$]	PWRs			27				13	
	BWRs			354				171	
	HWRs			2 050				252	
	GCRs			1 560				1 240	
	LWGRs			1 720				465	
	FBRs			380				209	
	All			330				120	

Table 32
Tritium released from reactors in airborne effluents

Country/reactor	*Release (GBq)*							
	1990	*1991*	*1992*	*1993*	*1994*	*1995*	*1996*	*1997*
PWRs								
Armenia								
Armenia 2								
Belgium [M1]								
Doel 1-4	752	548	774	2 020	1 990	613	287	227
Tihange 1-3	-	-	-	12 800	4 950	5 970	4 420	5 050
Brazil [C7]								
Angra 1	5.85	27.8	2 930	611	2.26	17.4	110	3 480
Bulgaria [C6]	Not reported							
Kozloduy 1-6								
China [C8, T2]								
Guangdong 1-2	-	-	-		330	232	411	
Qinshan	-	-		26.6	193	264	405	
Maanshan 1-2	847	2 270	5 330	6 290	5 110	6 590	5 580	8 430
Czech Republic [N2]								
Dukovany 1-4	447	432	416	325	466	410	412	308
Finland [F1]								
Loviisa 1-2	740	480	230	210	210	190	220	250
France [E1]	Amounts included with noble gases (Table 31)							
Belleville 1-2								
Blayais 1-4								
Bugey 2-5								
Cattenom 1-4								
Chinon B1-B4								
Chooz-A (Ardennes)								
Chooz B1-B2								
Cruas 1-4								
Dampierre 1-4								
Fessenheim 1-2								
Flamanville 1-2								
Golfech 1-2								
Gravelines 1-6								
Nogent 1-2								
Paluel 1-4								
Penly 1-2								
St. Alban 1-2								
St. Laurent B1-B2								
Tricastin 1-4								
Germany [B3]								
Biblis A-B	590	550	610	690	580	530	220	490
Brokdorf	110	220	180	210	330	350	370	320
Emsland	480	670	510	780	1 300	1 600	2 000	1 900
Grafenrheinfeld	460	440	540	610	520	520	550	290
Greifswald	0	68	10	12	20	7.6	2.6	1.7
Grohnde	760	730	500	720	530	360	680	190
Isar 2	890	950	1 300	1 400	1 300	1 300	1 300	970
Mülheim-Kärlich	270	180	150	100	110	90	80	40
Neckarwestheim 1-2	1 090	1 230	900	980	630	600	450	390
Obrigheim	230	100	130	130	72	99	150	130
Philippsburg 2	1 600	1 400	1 500	1 200	1 100	960	970	1 100
Stade	1 100	430	340	400	670	790	330	2 100
Unterweser	1 100	1 200	410	480	1 100	1 300	560	350
Hungary [F2]								
Paks 1-4	480	2 100	3 400	4 000	4 500	4 630	4 330	4 780

Table 32 (continued)

Country/reactor	*Release (GBq)*							
	1990	*1991*	*1992*	*1993*	*1994*	*1995*	*1996*	*1997*
Japan [J1, J5]								
Genkai 1-4	700	540	580	560	1 100	690	850	880
Ikata 1-3	450	410	490	710	620	730	810	730
Mihama 1-3	6 000	6 500	7 100	8 100	6 900	6 800	6 700	6 200
Ohi 1-4	1 900	3 900	3 800	4 700	8 000	6 300	8 300	7 500
Sendai 1-2	360	320	530	420	550	640	750	650
Takahama 1-4	2 600	2 900	4 600	5 200	5 400	5 900	8 200	8 400
Tomari 1-2	370	270	500	360	280	350	430	510
Tsuruga 2	900	1 200	720	1 400	2 300	2 300	2 200	3 400
Netherlands [N7]								
Borssele	446	210	353	565	386	343	371	177
Republic of Korea [K1]								
Kori 1-4	10 000	7 580	12 500	8 760	9 100	14 000	15 200	14 000
Ulchin 1-2	346	825	1 250	1 120	1 900	1 900	1 900	3 590
Yonggwang 1-4	592	3 050	1 930	1 820	3 400	8 100	8 800	8 660
Russian Federation [M6]								
Balakovo 1-4								
Kalinin 1-2								
Kola 1-4	Reported to be ≈ 0							
Novovoronezh 2-5								
Slovakia [N2, S4]								
Bohunice 1-4	963	1 045	1 066	924	890	1 090	922	581
Slovenia [S1]								
Krsko	2 460	2 050	1 510	1 960	1 720	1 310	1 160	1 050
South Africa [C11]								
Koeberg 1-2	3 640	7 070	5 610	5 270	3 130	2 840	4 610	10 200
Spain [C2]								
Almaraz 1-2	1 300	4 180	6 970	10 100	5 450	5 660	5 260	6 370
Asco 1-2	1 322	1 144	1 103	1 185	2 121	19 410	3 550	2 290
José Cabrera 1	517	266	661	193	34.9	25.3	26.6	88.9
Trillo 1	0	0	355	239	904	902	877	743
Vandellos 2	170	85.8	34.7	25.3	42.6	84.2	56.7	180
Sweden [N3]								
Ringhals 2-4	Not measured							
Switzerland [F3]								
Beznau 1-2								
Gösgen	Not measured							
Ukraine [G3]								
Khmelnitski 1								
Rovno 1-3								
South Ukraine 1-3	Reported to be ≈ 0							
Zaporozhe 1-6								
United Kingdom [M7]								
Sizewell B	-	-	-	-	-	-	579	565
United States [T3]								
Arkansas One 1-2	478	869	1 120	644	852	1 130	959	825
Beaver Valley 1-2	3 240	4 960	8 030	12 800	12 400	12 800	13 100	9 070
Braidwood 1-2	3 180	3 610	10 000	1 440	1 280	525		
Byron 1-2	39.6	33.3	114	34		158	1 380	
Callaway 1	1 370	1 360	1 950	3 370	3 310	3 690	3 240	2 980
Calvert Cliffs 1-2	16.7	428	362	909	46.3	93.0	98.9	213
Catawba 1-2	3 370	4 610	6 150	4 230	3 450	5 270	6 850	6 280
Comanche Peak 1-2	225	86.2	112	222	316	857	1 625	2 160
Crystal River 3	980	500	555	488	1 550		576	
Davis-Besse 1	1 070	2 390	799	829	831	779	1 350	1 310
Diablo Canyon 1-2	2 070	3 470	5 110	5 770	16 900	5 440	4 660	5 110
Donald Cook 1-2	366	1 070	725	955	1 370	3 490	3 300	10 900

Table 32 (continued)

Country/reactor	*Release (GBq)*							
	1990	*1991*	*1992*	*1993*	*1994*	*1995*	*1996*	*1997*
United States *(continued)*								
Farley 1-2	3 240	5 140	3 490	2 680	3 970	1 410	1 830	3 360
Fort Calhoun 1	273	12.6	225	44	9.9	30.5	144	
R. E. Ginna	4 590	3 090	2 130	1 910	1 630	1 940	1 520	
Haddam Neck	2 890	11 500	6 960	2 380				
Harris 1	57.7	30.0	16.2	1 880	0.5	25.5	924	340
Indian Point 1-3	116	281	225	182				
Kewaunee	221	289	451	60	161	2 430	819	58
Maine Yankee	1 380	338	147	270	770	1 170	378	1 110
McGuire 1-2	1 850	2 390	2 220	3 060	2 120	2 180	2 570	3 010
Millstone 2-3	4 060	3 570	3 690	4 060	1 390	43.6	1 810	618
North Anna 1-2	1 150	1 810	1 830	1 720	4 100	7 500	1 300	2 900
Oconee 1-2-3	3 740	4 030	2 390	1 640	1 590	1 600	2 650	2 420
Palisades	206	181	231	314	233	381	390	420
Palo Verde 1-3	27 900	49 300	36 400	47 100	55 200	43 800	70 000	
Point Beach 1-2	4 740	4 180	3 660	5 290	3 030	3 140	2 710	5 510
Prairie Island 1-2	4 660	2 600	1 570	2 330	2 480	1 460	1 600	1 200
Rancho Seco 1	1 080	703	681	279				
H. B. Robinson 2	164	166	158	294	206	542	445	505
Salem 1-2	5 710	4 110	5 250	6 250	2 530	1 250	6 920	11 700
San Onofre 1-3	4 590	1 650	2 870	2 290	1 970	1 580	1 080	2 460
Seabrook 1	9.32	507	58.1	23.4				
Sequoyah 1-2	433	1 070	1 850	1 470	548		2 350	
South Texas 1-2	1 530	847	3 970	541	5 990	6 300	5 450	1 390
St. Lucie 1-2	3 910	4 160	2 240	924	1 070	2 750		
Surry 1-2	800	900	900	900	600	600	800	1 500
Three Mile Island 1	1 220	18 100	3 520	6 780	601	694	388	4 800
Trojan	3 410	7 330	1 090	1 600	1 610	2 090	401	526
Turkey Point 3-4	2 940	10.8	1.47	306	53.1			
Virgil C. Summer 1	84.4	308	9.14	82.9	1 120	345	514	207
Vogtle 1-2	7 960	7 230	7 890	8 260	4 380	10 600	6 390	3 900
Waterford 3	7 590	16 200	11 500	3 770	5 590	4 510	3 330	7 290
Watts Bar	-	-	-	-			317	
Wolf Creek	690	555	640	951			1 490	
Yankee NPS	138	231	108	48	31	18.6	14.3	9.78
Zion 1-2	666	2 630	2 090	9 880	4 810	5 000	10 500	87.0
BWRs								
China [T2]								
Chin Shan 1-2	833	1 230	662	821	1 340	1 250	1 930	1 590
Kuosheng 1-2	1 290	2 500	1 760	1 540	1 250	1 080	765	535
Finland [F1]								
Olkiluoto 1-2	100	130	350	430	310	130	210	300
Germany [B3]								
Brunsbüttel	89	62	99	32	22	19	40	35
Gundremmingen B,C	200	380	470	300	470	1 300	2 200	1 200
Isar 1	430	560	74	82	88	44	56	60
Krümmel	79	99	51	31	13	45	46	42
Philippsburg 1	52	61	130	66	75	81	71	54
Würgassen	95	390	290	200	150	23	9.3	6
India [B4]								
Tarapur 1-2								
Japan [J1, J5]								
Fukushima Daiichi 1-6	2 500	2 100	1 900	1 500	1 600	1 600	1 500	1 900
Fukushima Daini 1-4	1 100	1 100	1 200	1 200	1 200	1 400	1 600	1 500
Hamaoka 1-4	820	730	720	780	570	640	810	860
Kashiwazaki Kariwa 1-7	510	560	660	790	1 100	1 400	1 700	2 000
Onagawa 1-2	190	210	190	200	210	210	310	370
Shika 1	-	-	0	13	66	90	79	100
Shimane 1-2	310	410	750	880	990	820	870	770
Tokai 2	580	560	570	550	570	390	460	420
Tsuruga 1	270	250	220	160	140	170	160	160

Table 32 (continued)

Country/reactor	*Release (GBq)*							
	1990	*1991*	*1992*	*1993*	*1994*	*1995*	*1996*	*1997*
Mexico [C5]								
Laguna Verde 1-2	0	105	73	540	657	1 520	651	1 180
Netherlands [N7]								
Dodewaard	10.8	119	71.8	39.6	15.2	25.9	9.5	11.2
Spain [C2]								
Confrentes	35.6	33.1	178	496	497	290	459	1 180
S. Maria de Garona	497	882	312	347	273	543	370	264
Sweden [N3]								
Barsebeck 1-2	Not measured							
Forsmark 1-3								
Oskarshamn 1-3								
Ringhals 1								
Switzerland [F3]								
Leibstadt						220	330	590
Mühleberg								
United States [T3]								
Big Rock Point	179	175	122	84.7	100	77	96.6	85.5
Browns Ferry 1-3	22	102	703	346	1 290			
Brunswick 1-2	984	718	400	740	836	1 350	999	860
Clinton 1	70	193	176	422	1 160	570	440	126
Cooper	0	0	0	0	0	0	0	0
Dresden 2-3	485	236	191	261	213	177	97.4	221
Duane Arnold 1	603	514	278	1 370	436	547	423	2 690
Enrico Fermi 2	0	0	1 070	87	0	0	0	0
Fitzpatrick	448	188	53	293	295	271	701	3 770
Grand Gulf 1	123	206	328	847	1 970	1 680	3 250	5 770
Hatch 1-2	1 480	1 260	1 850	2 450	2 660	1 610	793	630
Hope Creek 1	3 030	903	836	6 140	160	11.6	702	237
Lasalle 1-2	6.29	25	1 360	4 810	4 870	4 330		
Limerick 1-2	-	-	-	31	0	0		
Millstone 1	1 430	1 210	1 450	944	218	10.8	0	0
Monticello	3 160	2 380	3 850	2 060	2 680	1 570	807	556
Nine Mile Point 1-2	2 060	1 140	2 060	3 570	4 320			
Oyster Creek	424	283	404	136	1 310	440	558	5 500
Peach Bottom 2-3	1 150	1 480	1 470	844	388	6 170	11 400	
Perry 1	0	0	2.11	0	0	24.3	0	
Pilgrim 1	588	805	850	670	1 330	1 770	2 690	
Quad Cities 1-2	4 290	5 550	1 670	1 690	1 050	1 150	1 920	1 570
River Bend 1	1 670	507	86.2	200	344	90	106	2 720
Susquehanna 1-2	3 420	1 710	1 940	1 610	1 990	2 300	3 100	250
Vermont Yankee	3 580	3 130	948	877	813	824	902	2 050
WPPSS 2	1 370	448	1 780	5 550	370	211	285	596
HWRs								
Argentina [C3]								
Atucha 1	620 000	230 000	410 000	2 600 000	1 400 000	53 000	1 100 000	1 300 000
Embalse	75 000	55 000	69 000	140 000	130 000	83 000	69 000	77 000
Canada [A2]								
Bruce 1-4	1 628 000	1 193 000	1 100 000	1 650 000	999 000	610 000	700 000	350 000
Bruce 5-8	777 000	385 000	340 000	391 000	366 000	230 000	310 000	270 000
Darlington 1-4	118 000	231 000	110 000	130 000	330 000	270 000	200 000	190 000
Gentilly 2	227 000	270 000	322 000	200 000	258 000	310 000	220 000	160 000
Pickering 1-4	629 000	635 000	592 000	518 000	481 000	590 000	370 000	440 000
Pickering 5-8	277 000	183 000	192 000	244 000	226 000	190 000	190 000	170 000
Point Lepreau	250 000	170 000	400 000	640 000	520 000	310 000	240 000	200 000
India [B4]								
Kakrapar 1								
Kalpakkam 1-2	830 000	854 000	1 119 000	2 100 000	1 620 000			
Narora 1-2	66 000	182 500	244 600	118 400	264 700			
Rajasthan 1-2	2 561 000	1 768 000	820 000	703 300	765 900			

Table 32 (continued)

Country/reactor	*Release (GBq)*							
	1990	*1991*	*1992*	*1993*	*1994*	*1995*	*1996*	*1997*
Japan [J1, J5] Fugen	1 200	1 300	1 600	1 200	1 800	1 300	1 000	1 200
Pakistan [P2] Karachi	89 400	77 300	56 800	281 000	220 000	309 000	184 700	130 900
Republic of Korea [K1] Wolsong 1-2	231 000	257 000	389 000	368 000	480 000	440 000	310 000	625 000
Romania Cernavoda	-	-	-	-	-	-	1 370	25 500
United Kingdom [N5] Winfrith	8 390	3 990	4 620	4 250	10 930			366
GCRs								
France [E1] Bugey 1 Chinon A2-3 St. Laurent A1-2	Amounts included with noble gases (Table 31)							
Japan [J1, J5] Tokai 1	480	570	420	170	260	540	480	290
Spain [C2] Vandellos 1	0	0	0	0	0	0	0.002	
U. K. [M7, N4, N5]								
Berkeley			14	22	51	11	9.6	11
Bradwell			-	814	676	1 270	786	1 100
Calder Hall	2 760	2 640	3 210	3 000	5 100	5 600		4 400
Chapelcross								
Dungeness A			-	-	145	620	1 030	570
Dungeness B1-B2			-	-	2 540	2 440	1 520	4 780
Hartlepool A1-A2			-	-	-	1 120	1 560	1 610
Heysham 1A-B, 2A-B	670	1 170	2 530	2 000	2 050	3 260	3 060	2 720
Hinkley Point A			1 570	1 550	2 610	2 620	2 100	2 980
Hinkley Point B, A-B			897	1 620	1 830	2 500	2 100	1 960
Hunterston A1	460	130	69	35	31	16	0.6	4.9
Hunterston B1-B2	5 800	2 900	2 600	4 600	2 900	5 000	2 180	2 810
Oldbury A			1 680	1 960	1 860	1 890	1 730	1 480
Sizewell A-B			-	-	990	1 470	871	639
Torness A-B	1 300	1 900	1 300	1 700	1 700	1 300	1 260	1 810
Trawsfynydd			-	79	134	155	63	277
Wylfa	12 810	10 190	9 030	7 790	14 980	10 300	6 700	5 290
LWGRs								
Lithuania Ignalina 1-2	Only average normalized release reported							
Russian Federation [M6] Bilibino 1-4 Kursk 1-4 Leningrad 1-4 Smolensk 1-3	Only average normalized release reported							
Ukraine [G3] Chernobyl 1-3								
FBRs								
France Creys-Malville Phenix								
Kazakhstan Bn-350								

Table 32 (continued)

Country/reactor	*Release (GBq)*							
	1990	*1991*	*1992*	*1993*	*1994*	*1995*	*1996*	*1997*
Russian Federation								
Beloyarsky 3								
United Kingdom [N5]								
Dounreay PFR	3 200	3 100	2 300	3 700	2 000	1 700	790	570

Summary parameter	*Reactor*	*Release (TBq)*							
		1990	*1991*	*1992*	*1993*	*1994*	*1995*	*1996*	*1997*
All reactors									
Total release (TBq)	PWRs	168	236	217	239	230	243	260	196
	BWRs	40.6	35.7	34.6	47.0	40.4	38.7	43.9	42.8
	HWRs	8 388	6 496	6 171	10 090	6 615	3 873	3 896	39 400
	GCRs	24.3	19.5	23.3	25.3	37.9	40.1	25.5	32.7
	LWGRs								
	FBRs	3.2	3.1	2.3	3.7	2.0	1.7	0.79	0.57
	All	8 624	6 791	6 448	10 400	6 925	4 196	4 226	4 212
Annual normalized release [TBq (GW a)$^{-1}$]	PWRs	1.9	2.6	2.3	2.5	2.4	2.5	2.6	2.2
	BWRs	1.0	0.86	0.85	1.1	0.90	0.75	0.94	0.91
	HWRs	850	569	578	813	481	317	331	340
	GCRs	7.6	5.3	3.9	3.8	4.7	4.7	3.5	3.5
	LWGRs								
	FBRs	52	35	-	36	53	-	-	-
	All	62	46	42	65	42	25	25	27
Average normalized release 1990-1994 and 1995-1997 [TBq (GW a)$^{-1}$]	PWRs	2.3					2.4		
	BWRs	0.94					0.86		
	HWRs	650					329		
	GCRs	4.7					3.9		
	LWGRs	26					26		
	FBRs	49					-		
	All	51					26		

Table 33
Iodine-131 released from reactors in airborne effluents

Country/reactor	*Release (GBq)*							
	1990	*1991*	*1992*	*1993*	*1994*	*1995*	*1996*	*1997*
PWRs								
Armenia [A5]								
Armenia 2							0.331	0.365
Belgium [M1]								
Doel 1-4	0.485	0.657	0.192	0.097	0.01	0.032	0.008	0.0057
Tihange 1-3	0.295	0.086	0.039	0.027	0.016	0.0055	0.052	0.016
Brazil [C7]								
Angra 1		0.00047	0.356	0.481		0.00036	0.299	0.936
Bulgaria [C6]								
Kozloduy 1-6	5.6	4.5	10.6	8.0	2.2	1.50	1.98	2.68
China[C8, T2]								
Guangdong 1-2	-	-	-		0.424	0.720	0.229	0.116
Qinshan	-	-						
Maanshan 1-2	0	0	0	0	0	0	0	0
Czech Republic [N2]								
Dukovany 1-4	0.01	0.014	0.06	0.097	0.024	0.013	0.122	0.011
Finland [F1]								
Loviisa 1-2	0.017	0.16	0.025	0.033	0.00017	0.77	0.00087	0.000072
France [E1]								
Belleville 1-2								
Blayais 1-4								
Bugey 2-5								
Cattenom 1-4								
Chinon B1-B4								
Chooz-A (Ardennes)								
Chooz B1-B2								
Cruas 1-4								
Dampierre 1-4	Amounts included with particulates (Table 34)							
Fessenheim 1-2								
Flamanville 1-2								
Golfech 1-2								
Gravelines 1-6								
Nogent 1-2								
Paluel 1-4								
Penly 1-2								
St. Alban 1-2								
St. Laurent B1-B2								
Tricastin 1-4								
Germany [B3]								
Biblis A-B	0.0032	0.0015	0.024	0.012	0.042	0.017	0.030	0.0069
Brokdorf	0.0007	0.00084	0	0	0.00035	0.026	0.0006	0.0032
Emsland	0	0	0.000074	0.00034	0.0026	0.0013	0	0
Grafenrheinfeld	0.0022	0.0011	0.0028	0	0.000041	0	0.00015	0.0013
Greifswald	5.2	0	0	0	0	0	0	0
Grohnde	0	0	0.0013	0.0007	0.005	0.031	0.0082	0
Isar 2	0	0	0.00054	0	0	0	0	0
Mülheim-Kärlich	0	0	0	0	0	0	0	0
Neckarwestheim 1-2	0.0262	0.000082	0.00096	0.0067	0.0193	0.02	0.00071	0.0042
Obrigheim	0.00004	0.0001	0	0.031	0.000052	0.0087	0.000006	0.00007
Philippsburg 2	0	0.00018	0.00042	0	0.018	0.00074	0.00043	0.0045
Stade	0.0028	0.061	0.034	0.0031	0.00021	0.00026	0.002	0.004
Unterweser	0.00029	0.000056	0.00076	0	0.0001	0.0019	0.000097	0.00047
Hungary [F2]								
Paks 1-4	0.45	0.63	0.14	0.28	0.14	0.18	0.34	0.36

Table 33 (continued)

Country/reactor	*Release (GBq)*							
	1990	*1991*	*1992*	*1993*	*1994*	*1995*	*1996*	*1997*
Japan [J1, J5]								
Genkai 1-4	0	0	0	0	0	0	0	0
Ikata 1-3	0	0	0.0095	0	0	0	0	0
Mihama 1-3	0.0015	0.0061	0.019	0.010	0.0003	0.0002	0	0.0018
Ohi 1-4	0.0009	0.0011	0.0034	0.0003	0.0002	0	0	0.0009
Sendai 1-2	0	0	0	0	0	0	0	0
Takahama 1-4	0.0003	0.22	0.043	0.0004	0.0003	0.0002	0	0.0038
Tomari 1-2	0	0	0	0	0	0	0	0
Tsuruga 2	0	0	0	0	0	0	0	0
Netherlands [N7]								
Borssele	0	0.046	0	0.017	0.029	0.0095	0	0.03
Republic of Korea [K1]								
Kori 1-4	0.14	0.19	1.8	13.2	0.066	0.0170	0.0046	0.0078
Ulchin 1-2	0.19	0.0086	0.00022	0.0043	0.00052	0.00019	0.030	0.86
Yonggwang 1-4	0.00033	0.0077	0.0015	0.0062	0.018	0.156	0.017	0.011
Russian Federation [M6]								
Balakovo 1-4	1.55	0.16	0.32	1.62	0.12	0.14	0.68	0.13
Kalinin 1-2	1.02	0.11	0.19	0.41	0.54	0.68	0.14	0.07
Kola 1-4	2.07	3.78	11.61	5.54	3.11	3.65	1.89	3.30
Novovoronezh 2-5	0.71	2.70	0.27	0.14	0.27	0.41	1.08	1.10
Slovakia [N2, S4]								
Bohunice 1-4	1.72	1.79	1.43	1.59	1.38	2.05	1.88	0.87
Slovenia [S1]								
Krsko	0.012	0.007	0.096	0.41	0.30	0.75	2.74	1.45
South Africa [C11]								
Koeberg 1-2	0.55	1.28	0.56	0.32	0.26	0.31	0.13	0.16
Spain [C2]								
Almaraz 1-2	0.0006	0.124	0.026	0.011	0.014	0.014	0.089	0.095
Asco 1-2	0.025	0.0125	0.008	0.013	0.007	0.048	0.0002	0.00033
José Cabrera 1	0.903	1.49	4.84	0.702	0.025	0.003	0.008	0.18
Trillo 1	0.021	0	0	0.007	0	0	0	0.31
Vandellos 2	0.255	0.009	0.12	0.083	0.034	0.029	0.026	0.052
Sweden [N3]								
Ringhals 2-4	1.26	0.506	0.882	0.354	0.163	0.093	0.078	0.020
Switzerland [F3]								
Beznau 1-2	0.24	0.015	0.016	0.015	0.027	0.018	0.025	0.056
Gösgen	0.041	-	0.004	0.004	0.007	0.040	0.010	0.073
Ukraine [G3]								
Khmelnitski 1	0.44	0.45	1.37	0.57	0.13	0.30	0.57	0.32
Rovno 1-3	3.92	0.95	1.47	1.10	0.51	1.39	1.61	0.84
South Ukraine 1-3	0.012	0.021	0.012	0.0014	0.007	0.009	0.028	0.011
Zaporozhe 1-6	0.1	0.27	2.44	3.33	2.4	1.2	1.89	4.8
United Kingdom [M7]								
Sizewell B	-	-	-	-	-	-	0.049	0.034
United States [T3]								
Arkansas One 1-2	0.0074	0.081	0.036	0.0002	-	0.040	0.007	0.00008
Beaver Valley 1-2	0.0051	0.26	0.028	0.25	0.014	0.091	0.47	0.041
Braidwood 1-2	0.077	0.40	0.0014	0.12	0.14	0.031		
Byron 1-2	0.15	0.0063	0.016	0.016		0.024	0.017	
Callaway 1	0.0053	0.0006	0.017	0.023	0.00056	0.0016	0.0030	0.0007
Calvert Cliffs 1-2	0.054	0.49	0.62	0.52	0.16	0.067	0.020	0.037
Catawba 1-2	0.051	0.067	0.021	0.027	0.016	0.014	0	0
Comanche Peak 1-2	-	0.0007	0.031	0.0037	0	0	0.00005	0
Crystal River 3	0.028	0.0094	0.020	0.0007	0.00018		0.000009	
Davis-Besse 1	0.087	0.32	0.011	0.27	0.069	0.021	0.094	0.001
Diablo Canyon 1-2	0.0016	0.022	-	0.0002	0.15	0.23	0.074	0
Donald Cook 1-2	0.12	0.031	0.27	0.0028	0.35	0.33	0.23	0.076

Table 33 (continued)

Country/reactor	*Release (GBq)*							
	1990	*1991*	*1992*	*1993*	*1994*	*1995*	*1996*	*1997*
United States *(continued)*								
Farley 1-2	0.0001	0.060	0.0072	0	0.16	0.0046	0.0002	0.0049
Fort Calhoun 1	0.065	0.0075	0.011	0.0008	0.0015	0.11	1.02	
R. E. Ginna	0.19	0.059	0.052	0.027	0.0060	0.0027	0.0061	
Haddam Neck	0.094	0.62	0.0002	0.098				
Harris 1	-	-	0.023	0.0003	0.013	0.0016	0.00004	0.0020
Indian Point 1-3	0.17	0.014	0.48	0.18				
Kewaunee	0.00004	0.00001	-	-	0	-	0.14	0
Maine Yankee	0.16	0.24	0.14	0.15	0.028	0.011	0.0044	0.0004
McGuire 1-2	0.049	0.044	0.079	0.062	0.021	0.0023	0.00004	0
Millstone 2-3	1.25	0.93	0.31	0.052	0.030	0.67	0.0036	0
North Anna 1-2	0.23	0.094	0.50	0.090	0.015	0.009	0.004	0.007
Oconee 1-2-3	0.28	1.50	0.51	0.092	1.18	0.30	0.13	0.004
Palisades	0.069	0.0038	0.027	0.034	0.081	0.23	0.31	0.044
Palo Verde 1-3	0.20	1.22	0.46	0.42	0.22	0.36	0.23	
Point Beach 1-2	0.012	0.013	0.067	0.0045	0.0003	0.0041	0.0013	0
Prairie Island 1-2	0.053	0.0044	0.0070	0.025	0.001	0.019	0	0
Rancho Seco 1	-	-	-					
H. B. Robinson 2	0.000004	-	0.00004	0.054				
Salem 1-2	0.050	0.085	0.014	0.23	0.024	0.019	0	0
San Onofre 1-3	0.51	0.47	1.42	1.79	0.07	1.76	0.10	0.30
Seabrook 1	-	0.0007	0.0001	-				
Sequoyah 1-2	0.0073	0.0002	0.0002	0.00007	0.0003		0.00017	
South Texas 1-2	0.019	0.0068	0.082	0.0002	0.000001	0.0008	0.0014	0.064
St. Lucie 1-2	0.52	0.27	0.21	0.091	0.027	0.11		
Surry 1-2	0.049	0.019	0.018	0.023	0.15	0.081	0.010	0.14
Three Mile Island 1	0.057	0.037	0.18	0.27	0.049	0.20	0.00011	0.00008
Trojan	0.056	0.016	0.0084	0	0	0	0	0
Turkey Point 3-4	0.23	0.047	0.0080	0.084	0.18			
Virgil C. Summer 1	0.016	0.0087	0.0079	0.16	0.0078	0.00001	0.00006	0.00003
Vogtle 1-2	0.0010	0.074	0.050	0.017	0.030	0.030	0.22	0.076
Waterford 3	0.022	0.085	0.0007	0.00004	0.0040	0.029	0.00002	0.020
Watts Bar 1	-	-	-	-			0	
Wolf Creek	0.0031	0.089	0.0006	0.026			0.0033	
Yankee NPS	0.0050	0.0008	0.00008	0	0	0	0	0
Zion 1-2	0.048	0.28	1.77	0.41	0.0099	0.34	0.012	0
BWRs								
China [T2]								
Chin Shan 1-2	11.9	5.00	3.66	0.99	0.69	0.13	0.091	0.137
Kuosheng 1-2	0.102	0.0053	0.0011	0.0024	0.0034	0.052	0.0022	0.0030
Finland [F1]								
Olkiluoto 1-2	0.056	0.25	0.15	0.081	1.1	0.038	0.026	0.017
Germany [B3]								
Brunsbüttel	0.02	0.031	0.029	0	0	0.00094	0.017	0.0011
Gundremmingen B,C	0.015	0.00092	0.0021	0.00025	0.00036	0.00029	0.00014	0.00016
Isar 1	0.00055	0.00017	0.0016	0.023	0.035	0.013	0.023	0.057
Krümmel	0.06	0.077	0.32	0.15	0.036	0.38	0.22	0.14
Philippsburg 1	0.0014	0.0024	0.0033	0.12	0.59	0.05	0.047	0.075
Würgassen	0.019	0.16	0.098	0.036	0.045	0	0	0
India [B4]								
Tarapur 1-2	5.0	4.7	5.0	4.9	3.6			
Japan [J1, J5]								
Fukushima Daiichi 1-6	0.0083	0.0091	0.0072	0.0067	0.0028	0.0037	0.0032	0
Fukushima Daini 1-4	0	0	0	0	0	0	0	0.00002
Hamaoka 1-4	0.037	0	0	0	0	0	0	0
Kashiwazaki Kariwa 1-7	0	0	0	0	0	0	0	0
Onagawa 1-2	0	0	0	0	0	0	0	0
Shika 1	-	-	0	0	0	0	0	0
Shimane 1-2	0	0	0	0	0	0	0	0
Tokai 2	0	0	0	0	0	0	0	0
Tsuruga 1	0.0005	0.00006	0	0	0	0	0	0

Table 33 (continued)

Country/reactor	*Release (GBq)*							
	1990	*1991*	*1992*	*1993*	*1994*	*1995*	*1996*	*1997*
Mexico [C5]								
Laguna Verde 1-2	0.012	0.12	0.073	0.11	0.057	0.063	0.23	0.18
Netherlands [N7]								
Dodewaard	0.038	0.0035	0.0017	0.0014	0.0016	0.028	0.0024	0.0016
Spain [C2]								
Confrentes	0.032	3.05	1.48	0.604	0.38	0.128	0.052	0.24
S. Maria de Garona	0.015	0.031	0.012	0.105	0.083	0.091	0.031	0.011
Sweden [N3]								
Barsebeck 1-2	0.039	0.60	0.057	0.0062	0.0065	0.021	0.0027	0.0079
Forsmark 1-3	0.66	3.50	1.10	1.04	0.68	0.58	0.45	0.23
Oskarshamn 1-3	1.90	0.60	0.64	0.84	0.73	0.34	0.45	0.46
Ringhals 1	0.14	0.097	0.063	20.0	35.0	12.3	7.46	4.20
Switzerland [F3]								
Leibstadt	1.40	1.00	0.68	1.2	2.4	0.87	0.71	0.43
Mühleberg	0.15	0.018	0.021	0.012	0.013	0.0054	0.0053	0.02
United States [T3]								
Big Rock Point	0.077	0.049	0.16	0.095	0.12	0.04	0.17	0.02
Browns Ferry 1-3	-	0.36	0.51	0.19	0.50			
Brunswick 1-2	0.44	0.36	0.18	0.012	0.08	0.20	0.78	1.36
Clinton 1	0.0057	0.0011	0.0020	0.0047	0.0022	0.0036	0.016	0
Cooper	0.013	0.0037	0.0034	0.0010	0.0014	0.0016	0.71	0.65
Dresden 2-3	-	0.068	0.038	0.037	0.011	0.023	0.048	0.22
Duane Arnold 1	0.0096	0.0047	0.0034	0.0034	0.0034	0.0036	0.0029	0.0046
Enrico Fermi 2	0.13	0.090	0.15	0.23	0.0047	0.044	0.18	0.46
Fitzpatrick	0.073	0.096	0.0038	0.018	0.056	0.054	0.072	0.007
Grand Gulf 1	0.019	0.075	0.28	0.017	-	0.004	0.024	0.0003
Hatch 1-2	0.22	0.17	1.37	9.25	3.33	1.51	1.82	2.24
Hope Creek 1	0.044	-	-	-	0	0.024	0.015	0.020
Lasalle 1-2	0.080	0.065	0.052	1.10	0.12	0.17		
Limerick 1-2	0.0012	-	0.040	0.42	0.14	3.54		
Millstone 1	0.027	0.016	0.0083	0.052	0.012	0.056	0	0
Monticello	1.38	1.12	1.23	0.35	0.32	0.14	0.21	0.18
Nine Mile Point 1-2	0.053	0.19	0.090	0.17	0.015			
Oyster Creek	0.85	0.94	1.47	0.37	0.38	0.11	0.081	0.10
Peach Bottom 2-3	0.48	1.30	1.04	1.78	2.01	1.87	0.56	
Perry 1	0.36	0.51	5.62	1.47	0.48	1.01	0.30	
Pilgrim 1	0.34	1.42	1.19	1.14	0.50	0.23	0.26	0.21
Quad Cities 1-2	0.17	0.058	0.043	0.047	0.026	0.070	0.033	0.050
River Bend 1	1.79	1.45	0.30	0.81	1.78	1.40	0.51	0.90
Susquehanna 1-2	-	0.0005	0.0006	-	0.0004	0	0	0
Vermont Yankee	2.04	2.31	1.57	0.42	0.11	0.07	0.035	0.015
WPPSS 2	3.21	0.79	0.29	0.48	0.16	0.11	0.0023	
HWRs								
Argentina [C3]								
Atucha 1	0.078	1.3	0.0089	0.49	0.44	0.35	0.041	0.53
Embalse	1.4	1.6	0.07	0	0.26	1.7	0.27	0
Canada [A2]								
Bruce 1-4	0.063	0.055	0.040	0.033	0.030	0.027	0.019	0.014
Bruce 5-8	0.12	0.13	0.064	0.057	0.059	0.12	0.044	0.035
Darlington 1-4	0.012	0.016	0.018	0.031	0.036	0.034	0.022	0.020
Gentilly 2	0	0.019	0.0037	0.0037	0	0	0	0
Pickering 1-4	0.32	0.12	0.089	0.13	0.10	0.074	0.073	0.074
Pickering 5-8	0.089	0.063	0.052	0.048	0.085	0.10	0.098	0.099
Point Lepreau	0	0.016	0.0030	0.0002	0.0051	0	0.0015	0.021
India [B4]								
Kakrapar 1								
Kalpakkam 1-2	0.16	0.24	0.26	0.51	0.05			
Narora 1-2	0	0.02	1.55	2.30	2.97			
Rajasthan 1-2	1.43	1.00	0.46	0.78	0.31			

Table 33 (continued)

Country/reactor	*Release (GBq)*							
	1990	*1991*	*1992*	*1993*	*1994*	*1995*	*1996*	*1997*
Japan [J1, J5] Fugen	0	0	0	0	0	0	0	0
Pakistan [P2] Karachi	0	0	0	0	0	0	0	0
Republic of Korea [K1] Wolsong 1-2	0	0.0012	0.00037	0	0	0.0052	0.14	0
Romania Cernavoda	-	-	-	-	-	-	0	0.0071
United Kingdom [N5] Winfrith	0.22	0.38						
GCRs								
France [E1] Bugey 1 Chinon A2-3 St. Laurent A1-2	Amounts included with noble gases (Table 31)							
Japan [J1, J5] Tokai1	0.0020	0.0014	0.0006	0.00005	0	0.0016	0.0005	0
Spain [C2] Vandellos 1	0.0002	0.0001	0	0	0	0	0	
U. K. [M7, N4, N5]								
Berkeley	-	-	-					
Bradwell	-	-	-					
Calder Hall	0.58	0.57	1.05	0.61				
Chapelcross	-	-	-					
Dungeness A	-	-	-					
Dungeness B1-B2	1.9	2.0	3.0	6.0	0.4	0.3	0.004	0.004
Hartlepool A1-A2	0.3	0.2	0.3	0.3	0.3	0.3	0.3	0.19
Heysham 1A-B, 2A-B	1.5	1.5	1.5	1.4	1.4	1.5	1.4	1.40
Hinkley Point A	-	-	-					
Hinkley Point B, A-B	0.4	0.41	0.14	0.1	0.1	0.1	0.02	0.02
Hunterston A1	-	-	-					
Hunterston B1-B2	-	-	-					
Oldbury A	-	-	-					
Sizewell A	-	-	-					
Torness A-B	-	-	-					
Trawsfynydd	-	-	-					
Wylfa	-	-	-					
LWGRs								
Lithuania [E2] Ignalina 1-2	4.25	10.0	1.2	0.5	2.9	6.2	11.5	6.3
Russian Federation [M6]								
Bilibino 1-4	0	0	0	0	0	0	0	0
Kursk 1-4	7.47	1.08	3.51	7.29	3.65	6.75	9.99	10.7
Leningrad 1-4	20.7	36.3	88.8	19.6	30.3	19.6	29.2	17.5
Smolensk 1-3	3.41	3.92	9.99	16.5	12.2	6.21	5.67	23.8
Ukraine [G3] Chernobyl 1-3	10.8	6.77	2.85	7.96	4.66	5.40	7.84	1.96
FBRs								
France [E1] Creys-Malville Phenix	Not reported							
Kazakhstan Bn-350								

Table 33 (continued)

Country/reactor	*Release (GBq)*							
	1990	*1991*	*1992*	*1993*	*1994*	*1995*	*1996*	*1997*
Russian Federation [M6] Beloyarsky 3	0	0	0	0	0	0	0	
United Kingdom [N5] Dounreay PFR								

Summary parameter	*Reactor*	*Release (GBq)*							
		1990	*1991*	*1992*	*1993*	*1994*	*1995*	*1996*	*1997*
All reactors									
Total release (GBq)	PWRs	32.3	28.2	60.7	44.1	15.3	19.7	19.4	20.1
	BWRs	33.4	30.7	29.1	49.1	55.6	25.8	15.6	12.6
	HWRs	3.90	4.96	2.62	4.39	4.35	2.41	0.71	0.80
	GCRs	4.68	4.68	5.99	8.41	2.20	2.20	1.72	1.62
	LWGRs	46.6	58.1	106	51.9	53.7	44.2	64.2	60.3
	FBRs	-	-	-	-	-	-	-	-
	All	121	127	205	158	131	94.2	102	95.4
Annual normalized release [GBq (GW a)$^{-1}$]	PWRs	0.31	0.26	0.54	0.40	0.14	0.18	0.16	0.19
	BWRs	0.74	0.62	0.60	0.98	1.1	0.45	0.30	0.26
	HWRs	0.39	0.44	0.25	0.35	0.32	0.20	0.06	0.07
	GCRs	1.8	1.4	1.5	1.8	0.49	0.56	0.37	0.35
	LWGRs	4.4	5.6	12	5.5	7.1	5.5	7.3	7.7
	FBRs								
	All	0.70	0.69	1.1	0.84	0.69	0.48	0.52	0.53
Average normalized release 1990-1994 and 1995-1997 [GBq (GW a)$^{-1}$]	PWRs			0.33				0.17	
	BWRs			0.81				0.33	
	HWRs			0.35				0.11	
	GCRs			1.4				0.42	
	LWGRs			6.8				6.9	
	FBRs								
	All			0.81				0.51	

Table 34
Particulates released from reactors in airborne effluents

Country/reactor	*Release (GBq)*							
	1990	*1991*	*1992*	*1993*	*1994*	*1995*	*1996*	*1997*
PWRs								
Armenia [A5]								
Armenia 2							2.34	2.77
Belgium [M1]								
Doel 1-4	0.162	0.1	0.075	0.008	0.0006	0.0036	0.0028	0.0015
Tihange 1-3	0.136	0.077	0.017	0.020	0.032	0.051	0.033	0.015
Brazil [C7]								
Angra 1			0.000009	0.000007	0.0000001	0	0.01	0.044
Bulgaria [C6]								
Kozloduy 1-6	2.4	1.7	3.8	2.3	2.0	1.50	1.92	1.86
China [C8, T2]								
Guangdong 1-2	-	-	-					
Qinshan	-	-						
Maanshan 1-2	0	0	0.016	0.0044	0.0037	0.011	0.0019	0.011
Czech Republic [N2]								
Dukovany 1-4	0.099	0.10	0.21	0.21	0.15	0.13	0.080	0.24
Finland [F1]								
Loviisa 1-2	0.2	0.17	0.28	0.081	0.23	0.34	0.22	0.25
France [E1]								
Belleville 1-2	0.59	0.39	0.57	2.2	0.18	0.21	0.25	0.089
Blayais 1-4	0.52	0.33	0.53	0.31	0.44	0.80	0.33	0.11
Bugey 2-5	0.54	0.93	0.44	0.44	0.38	0.32	0.33	0.38
Cattenom 1-4	0.25	0.19	0.35	0.23	0.22	0.17	0.18	0.17
Chinon B1-B4	1.0	1.4	0.90	0.30	0.86	0.41	0.099	0.069
Chooz-A (Ardennes)	0.099	0.88	0.019	0.012	0.012	0.006	0.0004	0.0002
Chooz B1-B2							0.039	0.87
Cruas 1-4	0.21	0.14	0.11	0.25	0.52	0.17	0.14	0.059
Dampierre 1-4	0.55	0.37	0.37	0.84	0.69	1.1	0.099	0.10
Fessenheim 1-2	0.029	0.039	0.029	0.029	0.019	0.019	0.039	0.029
Flamanville 1-2	0.12	0.19	0.48	0.12	0.25	0.10	0.12	0.12
Golfech 1-2	0.049	0.029	0.019	0.028	0.019	0.039	0.19	0.80
Gravelines 1-6	1.4	1.1	0.75	1.1	2.1	4.3	0.55	0.35
Nogent 1-2	0.18	0.099	0.28	0.65	0.17	0.15	0.25	0.15
Paluel 1-4	0.26	0.39	0.24	0.18	1.3	0.54	0.33	0.13
Penly 1-2	0.019	0.019	0.049	0.087	0.31	0.039	0.096	0.12
St. Alban 1-2	0.089	0.29	0.11	0.12	0.089	0.59	0.13	0.11
St. Laurent B1-B	0.089	0.029	0.039	0.039	0.039	0.079	0.074	0.099
Tricastin 1-4	0.40	0.44	0.35	0.33	0.13	0.13	0.11	0.19
Germany [B3]								
Biblis A-B	0.011	0.024	0.014	0.01	0.03	0.0025	0.0020	0.0084
Brokdorf	0.00037	0.0012	0	0.0014	0.00045	0	0	0
Emsland	0.0006	0.00039	0.00037	0.000071	0.00068	0.000007	0.00066	0.00017
Grafenrheinfeld	0.0083	0.0033	0.0019	0.0015	0.0016	0.0027	0.0026	0.002
Greifswald	0.62	0.12	0.063	0.038	0.021	0.28	0.16	0.087
Grohnde	0.0001	0	0.00059	0.00029	0.0011	0.00025	0.00096	0.0012
Isar 2	0.000037	0.000013	0.00034	0.000036	0	0	0.0018	0.00007
Mülheim-Kärlich	0	0	0	0	0	0	0	0
Neckarwestheim 1-2	0.0063	0.0034	0.0026	0.0016	0.0071	0.0012	0.0029	0.00027
Obrigheim	0.004	0.0086	0.0049	0.012	0.012	0.018	0.0092	0.0074
Philippsburg 2	0.00045	0.00037	0.001	0.0018	0.0018	0.00099	0.00015	0.00053
Stade	0.046	0.021	0.0049	0.005	0.0042	0.079	0.0010	0.00024
Unterweser	0.0019	0.0021	0.001	0.00099	0.0014	0.0012	0.0015	0.00079
Hungary [F2]								
Paks 1-4	1.14	1.30	0.45	1.30	1.28	0.49	0.74	1.30

Table 34 (continued)

Country/reactor	*Release (GBq)*							
	1990	*1991*	*1992*	*1993*	*1994*	*1995*	*1996*	*1997*
Japan [J1, J5]								
Genkai 1-4	0	0	0	0	0	0	0	0
Ikata 1-3	0	0	0	0	0	0	0	0
Mihama 1-3	0	0	0	0	0	0	0	0
Ohi 1-4	0	0	0	0	0	0	0	0
Sendai 1-2	0	0	0	0	0	0	0	0
Takahama 1-4	0	0	0	0	0	0	0	0
Tomari 1-2	0	0	0	0	0	0	0	0
Tsuruga 2	0	0	0	0	0	0	0	0
Netherlands [N7]								
Borssele	0	0	0	0	0.0011	0	0	0
Republic of Korea [K1]								
Kori 1-4	0.12	0.015	0.0014	0.95	0.00007	0.00007	0.0027	0
Ulchin 1-2	0.024	0.00004	0.0016	0.00002	0.0077	0.015	0.0020	0.021
Yonggwang 1-4	0.00078	0.0011	0.00015	0	2.7	0.013	0.023	0.00062
Russian Federation [M6]								
Balakovo 1-4	1.49	0.14	0.27	0.41	0.24	0.14	0.18	0.12
Kalinin 1-2	0.03	0.03	0.03	0.20	0.14	0.05	0.11	0.09
Kola 1-4	8.51	7.16	2.57	3.24	2.97	2.03	0.92	0.20
Novovoronezh 2-5	1.88	2.43	0.95	1.07	0.68	2.43	2.30	1.54
Slovakia [N2, S4]								
Bohunice 1-4	0.38	0.54	1.46	1.1	0.37	0.53	0.30	0.54
Slovenia [S1]								
Krsko	0	0	0	0.0034	0.0004	0.020	0.00017	0.0036
South Africa [C11]								
Koeberg 1-2	1.04	4.50	2.18	3.79	4.97	6.22	3.31	4.19
Spain [C2]								
Almaraz 1-2	0.071	0.033	0.006	0.04	0.037	0.011	0.043	0.0079
Asco 1-2	0.032	0.02	0.025	0.028	0.024	0.219	0.016	0.036
José Cabrera 1	0.063	0.25	0.668	0.344	0.007	0.004	0.017	0.0088
Trillo 1	0.01	0.017	0.006	0.006	0.005	0.006	0.002	0.0022
Vandellos 2	0.019	0.017	0.027	0.021	0.037	0.004	0.008	0.025
Sweden [N3]								
Ringhals 2-4	0.017	0.014	0.0038	0.016	0.014	0.0051	0.00088	0.050
Switzerland [F3]								
Beznau 1-2	0.0015	0.0018	0.0041	0.00087	0.002	0.006	0.006	0.006
Gösgen	0.0024	0.0013	0.00067	0.006	0.006	0.010	0.010	0.010
Ukraine [G3]								
Khmelnitski 1	0.035	0.16	0.10	0.12	0.076	0.080	0.10	0.076
Rovno 1-3	0.33	0.30	0.48	0.18	0.17	0.39	0.13	0.16
South Ukraine 1-3	0.012	0.021	0.012	0.0014	0.007	0.009	0.028	0.011
Zaporozhe 1-6	0.13	0.15	0.28	0.28	0.17	0.17	0.12	0.08
United Kingdom [M7]								
Sizewell B	-	-	-	-	-	-	0.0087	0.0051
United States [T3]								
Arkansas One 1-2	0.033	1.59	1.84	0.00022	0.0004	0.15	0.0004	0.0002
Beaver Valley 1-2	0.019	0.11	0.029	0.56	0.045	0.73	0.048	0.029
Braidwood 1-2	0.0014	0.012	0	0	0	0		
Byron 1-2	0.0015	0.0004	0	0.00022		0.00086	0.0039	
Callaway 1	0.0001	0.00004	0.0058	0.039	0.00051	0.057	0.0002	0.0001
Calvert Cliffs 1-2	0.0091	0.0001	0.0020	0.28	0.044	0.0019	0.00009	0.00021
Catawba 1-2	0.013	0.036	0.036	0.0073	0.0034	0.14	0.00056	0.036
Comanche Peak 1-2	0.0014	0	0	0.00014	0	0	0.00008	0
Crystal River 3	0.0002	0.0075	0.0003	0.00025	0.00035		0.00023	
Davis-Besse 1	0.0011	0.0022	0.024	0.016	0.0020	0.00009	0.0052	0.001
Diablo Canyon 1-2	0.0006	0.00026	0.095	0.0017	0.013	0.0038	0.0057	0.001
Donald Cook 1-2	2.60	0.058	0.074	0.016	0.078	0.22	1.10	0.46

Table 34 (continued)

Country/reactor	*Release (GBq)*							
	1990	*1991*	*1992*	*1993*	*1994*	*1995*	*1996*	*1997*
United States *(continued)*								
Farley 1-2	0	0	0.0086	0.0011	0.50	0.00089	0.0004	0.00024
Fort Calhoun 1	0.0015	0.0044	0.01	0.00006	0.00011	0.00084	0.00026	
R. E. Ginna	0.0011	0.0019	0	0.00056	0.00023	0.00014	0.020	
Haddam Neck	0.080	0.34	0.20	0.36				
Harris 1	0.0029	0.0017	0.0070	0.0064	0.0041	0.34	0.0015	0.0089
Indian Point 1-3	0.036	0.064	0.0081	0.041				
Kewaunee	0.12	0.071	0.00006	0.0007	0.0017	0.00054	0.0013	0.00021
Maine Yankee	0.51	0.028	0.052	0.060	0.037	0.037	0.030	0.00095
McGuire 1-2	0.027	0.028	0.0067	0.0021	0.00024	0.0072	0.00006	0.0017
Millstone 2-3	0.0030	0.019	0.021	0.026	0.0054	0.0052	0.00028	0.0005
North Anna 1-2	0.022	0.0059	0.0037	0.017	0.0026	0.003	0.012	0.001
Oconee 1-2-3	0.052	0.041	0.011	0.031	0.11	0.015	0.01	0.014
Palisades	0.010	0.0073	0.0084	0.0077	0.0029	0.0035	0.0041	0.0032
Palo Verde 1-3	0.059	0.10	0.060	0.29	0.095	0.056	0.0095	
Point Beach 1-2	0.0083	0.12	0.41	0.54	0.08	0.16	0.0084	0.00008
Prairie Island 1-2	0.0026	0.014	0.0024	0.0026	0.0028	0.005	0.006	0.033
Rancho Seco 1	0	0	0	0				
H. B. Robinson 2	0.0050	0.0064	0.0051	0.0033	0.0001	0.0003	0.0013	0.0006
Salem 1-2	0.0021	0.0031	0.0025	0.00074	0.00073	0.00077	0.00098	0.00012
San Onofre 1-3	0.024	0.028	0.019	0.069	0.021	0.018	0.029	0.018
Seabrook 1	0	0.039	0.041	0.00002				
Sequoyah 1-2	0.0025	0.021	0.0032	0.00045	0		0.0016	
South Texas 1-2	0.045	0.084	0.013	0.020	0.0013	0.017	0.0057	0.0052
St. Lucie 1-2	0.0030	0.0070	0.0085	0.0046	0.020	0.0079		
Surry 1-2	0.059	0.022	0.011	0.0065	0.012	0.006	0.007	0.002
Three Mile Island 1	0.00014	0.0029	0.0012	0.00025	0.00046	0.00015	0.000001	0.0012
Trojan	0.0048	0.0054	0.0007	0	0	0	0	0
Turkey Point 3-4	0.0059	0.0013	0.0008	0	0.0016			
Virgil C. Summer 1	0.0043	0.0018	0	0.0048	0.014	0.00002	0.00025	0.0019
Vogtle 1-2	0.0020	0.0033	0.17	0.0021	0.0040	0.0091	0.012	0.00090
Waterford 3	0	0.0026	0.00037	0	0.0028	0.0027	0.00019	0.00080
Watts Bar	-	-	-	-			0	
Wolf Creek	0.0032	0	0.00005	0			0.00004	
Yankee NPS	0.0010	0.00035	0.00029	0.00003	0.00027	0.00091	0.00076	0.00003
Zion 1-2	0.0026	0.0070	0.12	0.87	0.035	0.14	0.060	0.032
BWRs								
China [T2]								
Chin Shan 1-2	0.71	0.22	0.080	0.039	0.11	0.038	0.020	0.012
Kuosheng 1-2	0.0039	0.075	0.015	0.0003	0.0003	0.0024	0	0.000007
Finland [F1]								
Olkilouto 1-2	0.22	0.74	0.3	0.11	0.13	0.033	0.014	0.045
Germany [B3]								
Brunsbüttel	0.054	0.023	0.075	0.041	0.034	0.034	0.034	0.026
Gundremmingen B,C	0	0	0	0	0	0	0.000074	0.000062
Isar 1	0.0063	0.0019	0.0087	0.011	0.018	0.010	0.016	0.013
Krümmel	0.0051	0.039	0.025	0.028	0.019	0.034	0.086	0.15
Philippsburg 1	0.073	0.023	0.022	0.08	0.054	0.032	0.021	0.025
Würgassen	0.045	0.17	0.058	0.077	0.053	0.013	0.012	0.041
India [B4]								
Tarapur 1-2	8.6	21.6	4.8	8.7	5.8			
Japan [J1, J5]								
Fukushima Daiichi 1-6	0.0081	0.0017	0.0010	0.0019	0.0034	0.0002	0.0006	0.0020
Fukushima Daini 1-4	0	0	0	0	0	0	0	0
Hamaoka 1-4	0	0	0	0	0	0	0	0
Kashiwazaki Kariwa 1-7	0	0	0	0	0	0	0	0
Onagawa 1-2	0	0	0	0	0	0	0	0
Shika 1	-	-	0	0	0	0	0	0
Shimane 1-2	0.0002	0.0004	0	0.0010	0.0003	0	0	0.0004
Tokai 2	0	0	0	0	0	0	0	0
Tsuruga 1	0	0.00005	0.0003	0.00004	0.00008	0	0.0001	0

Table 34 (continued)

Country/reactor	*Release (GBq)*							
	1990	*1991*	*1992*	*1993*	*1994*	*1995*	*1996*	*1997*
Mexico [C5]								
Laguna Verde 1-2	0.12	1.11	0.31	0.55	0.21	16.7	2.01	0.63
Netherlands [N7]								
Dodewaard	0.028	0.0086	0.0043	0.0045	0.0052	0.0049	0.0046	0.005
Spain [C2]								
Confrentes	0.153	0.545	0.415	0.077	0.066	0.049	0.005	0.46
S. Maria de Garona	0.071	0.032	0.046	0.139	0.216	0.077	0.127	0.015
Sweden [N3]								
Barsebeck 1-2	0.19	0.37	0.73	0.48	0.48	1.00	3.06	1.60
Forsmark 1-3	82.7	139	199	37.8	19.5	84.4	1.84	2.77
Oskarshamn 1-3	275	178	58.8	53.2	40.5	14.0	40.8	30.5
Ringhals 1	20.2	65.0	0.022	323	43 500	44 700	10 600	1 740
Switzerland [F3]								
Leibstadt	0.036	0.0071	0.0019	0.003	0.011	0.020	0.020	0.020
Mühleberg	0.049	0.078	0.013	0.01	0.007	0.020	0.020	0.020
United States [T3]								
Big Rock Point	0.13	0.065	0.026	0.046	0.12	0.09	0.13	0.14
Browns Ferry 1-3	0.0070	0.69	1.21	0.76	0.65			
Brunswick 1-2	1.35	0.35	0.097	0.28	0.78	0.83	0.24	0.36
Clinton 1	0.32	0.34	0.091	0.68	1.70	0.16	0.036	0.0025
Cooper	0.028	0.017	0.015	0.013	0.016	0.012	1.58	2.42
Dresden 2-3	5.45	1.45	0.84	1.38	0.58	0.52	0.079	0.30
Duane Arnold 1	0.16	0.093	0.11	0.077	0.030	0.11	0.064	0.014
Enrico Fermi 2	0.44	0.12	0.10	0.11	0.0052	0.052	0.056	0.12
Fitzpatrick	0.63	0.83	0.012	0.067	0.77	0.45	0.047	0.01
Grand Gulf 1	0.018	0.083	0.046	0.0031	0.0034	0.0032	0.0014	0.0059
Hatch 1-2	0.094	0.044	0.20	3.88	11.4	0.45	2.43	1.85
Hope Creek 1	0.16	0.016	0.099	0.072	0.0017	0.071	0.14	0.095
Lasalle 1-2	0.047	0.19	0.048	4.94	0.14	0.22		
Limerick 1-2	0.027	0.0042	0.015	0.63	17.8	0.17		
Millstone 1	0.070	0.076	0.047	0.14	0.23	0.42	0.021	0.016
Monticello	0.22	0.22	0.25	0.74	0.10	0.067	0.063	0.048
Nine Mile Point 1-2	0.23	0.59	0.32	0.37	0.13			
Oyster Creek	0.31	0.21	0.64	0.086	0.19	0.1	0.093	0.068
Peach Bottom 2-3	0.19	0.28	0.14	0.29	0.52	0.51	0.15	
Perry 1	0.052	0.011	0	0.085	2.62	0.21	0.75	
Pilgrim 1	0.036	0.32	0.52	0.47	0.25	0.87	0.089	0.087
Quad Cities 1-2	1.06	0.38	1.09	0.91	0.10	0.77	0.77	0.66
River Bend 1	0.13	0.19	0.044	0.052	0.13	0.14	0.13	0.24
Susquehanna 1-2	0.032	0.0085	0.17	0.048	0.07	0.06	0.029	0.054
Vermont Yankee	0.64	0.68	0.79	0.32	0.07	0.025	0.007	0.032
WPPSS 2	2.34	1.53	1.31	0.86	0.10	0.25	0.081	
HWRs								
Argentina [C3]								
Atucha 1	0.0011	0.015	0.015	0.18	0.049	0.013	0.038	0.006
Embalse	0	0.12	0.025	0	0.0036	0.077	0	0
Canada [A2]								
Bruce 1-4	0.081	0.063	0.072	0.079	0.11	0.12	0.072	0.070
Bruce 5-8	0.14	0.14	0.12	0.12	0.10	0.12	0.075	0.088
Darlington 1-4	0.012	0.046	0.046	0.11	0.10	0.085	0.058	0.065
Gentilly 2	0.00037	0.013	0.074	0.052	0.070	0.045	0.030	0.114
Pickering 1-4	0.29	0.087	0.089	0.085	0.070	0.070	0.051	0.355
Pickering 5-8	0.018	0.019	0.020	0.021	0.041	0.026	0.027	0.039
Point Lepreau	0	0	0.0040	0.0013	0.0005	0	0	0.00005
India [B4]								
Kakrapar 1								
Kalpakkam 1-2	0	0	0	0	0			
Narora 1-2	0	0	0	0	0			
Rajasthan 1-2	0.014	0.004	0.004	0.006	0.002			

Table 34 (continued)

Country/reactor	*Release (GBq)*							
	1990	*1991*	*1992*	*1993*	*1994*	*1995*	*1996*	*1997*
Japan [J1, J5]								
Fugen	0	0	0	0	0	0	0	0
Pakistan [P2]								
Karachi	0	0	0	0	0	0	0	0
Republic of Korea [K1]								
Wolsong 1-2	0	0	0	0	0	0	0	0
Romania								
Cernavoda	-	-	-	-	-	-	0	0
United Kingdom [N5]								
Winfrith	0.19		0.021	0.00002	0.00002			
GCRs								
France [E1]								
Bugey 1	0.43	0.38	0.29	0.17	0.30	0.38	0.009	0.005
Chinon A2-3	0.025	0.018	0.011	0.006	0.008	0.019	0.005	0.009
St. Laurent A1-2	0.21	0.13	0.14	0.011	0.005	0.002	0.001	0.0007
Japan [J1, J5]								
Tokai 1	0.0021	0.011	0.0002	0.0002	0.0013	0.0001	0.0002	0
Spain [C2]								
Vandellos 1	0.02	0.004	0.003	0.002	0.0008	0	0.002	
U. K. [M7, N4, N5]								
Berkeley	0.01	0.01	0.01	0.01	0.01	0.01	0.004	0.004
Bradwell	0.07	0.07	0.03	0.05	0.26	0.16	0.21	0.20
Calder Hall	-	-	-					
Chapelcross	-	-	-					
Dungeness A	0.17	0.11	0.13	0.21	0.26	0.4	0.33	0.30
Dungeness B1-B2	0.07	0.06	0.07	0.07	0.04	0.01	0.049	0.035
Hartlepool A1-A2	0.04	0.04	0.04	0.04	0.04	0.04	0.035	0.025
Heysham 1A-B, 2A-B	0.05	0.05	0.012	0.07	0.07	0.08	0.069	0.099
Hinkley Point A	0.30	0.23	0.15	0.23	0.23	0.16	0.077	0.17
Hinkley Point B, A-B	0.57	0.46	0.32	0.40	0.31	0.08	0.077	0.075
Hunterston A1	0.008	0.0016	0.0011	0.0036	0.0025	0.0013	0.0002	0.0002
Hunterston B1-B2	0.13	0.049	0.12	0.18	0.13	0.074	0.036	0.034
Oldbury A	0.05	0.07	0.10	0.10	0.08	0.10	0.091	0.10
Sizewell A-B	0.33	0.37	0.41	0.55	0.53	0.36	0.022	0.073
Torness A-B	0.045	0.027	0.013	0.026	0.071	0.014	0.015	0.015
Trawsfynydd	0.28	0.04	0.02	0.01	0.01	0.01	0.0016	0.0023
Wylfa	0.11	0.10	0.16	0.13	0.11	0.10	0.0087	0.074
LWGRs								
Lithuania [E2]								
Ignalina 1-2	9.8	1.06	2.2	1.5	8.2	4.2	7.8	1.3
Russian Federation [M6]								
Bilibino 1-4	0	0	0	0	0	0	0	0
Kursk 1-4	25.9	11.6	11.2	9.18	8.51	13.1	13.5	19.2
Leningrad 1-4	62.2	96.2	98.7	28.1	76.4	42.6	64.6	22.9
Smolensk 1-3	9.55	12.4	24.0	8.64	2.70	1.76	2.97	3.78
Ukraine [G3]								
Chernobyl 1-3	51.2	43.2	13.7	13.5	6.85	3.66	4.00	1.89
FBRs								
France [E1]								
Creys-Malville	0.008	0.012	0.011	0.011	0.012	0.013	0.013	0.013
Phenix								
Kazakhstan [A6]								
Bn-350	0.84	0.97	1.25	23.4	0.69	0.67	0.53	0.46

Table 34 (continued)

Country/reactor	*Release (GBq)*							
	1990	*1991*	*1992*	*1993*	*1994*	*1995*	*1996*	*1997*
Russian Federation [M6]								
Beloyarsky 3	0	0	0	0	0	0	0	0
United Kingdom								
Dounreay PFR								

Summary parameter	*Reactor*	*Release (GBq)*							
		1990	*1991*	*1992*	*1993*	*1994*	*1995*	*1996*	*1997*
All reactors									
Total release (GBq)	PWRs	29.2	29.6	22.9	26.3	25.2	26.5	17.7	18.2
	BWRs	402	416	273	442	43 610	44 820	10 660	1 783
	HWRs	0.75	0.51	0.49	0.65	0.55	0.56	0.35	0.74
	GCRs	2.92	2.33	2.14	2.27	2.47	2.00	1.04	1.22
	LWGRs	159	164	150	60.9	103	65.3	92.9	49.0
	FBRs	0.85	0.98	1.26	23.4	0.70	0.68	0.54	0.47
	All	595	614	450	555	43 740	44 920	10 770	1 852
Annual normalized release [GBq (GW a)$^{-1}$]	PWRs	0.21	0.20	0.15	0.17	0.17	0.17	0.11	0.12
	BWRs	8.4	8.0	5.5	8.6	826	781	204	36
	HWRs	0.076	0.044	0.046	0.053	0.040	0.046	0.030	0.070
	GCRs	0.43	0.32	0.27	0.25	0.27	0.24	0.14	0.13
	LWGRs	15	16	17	6.4	14	8.2	11	6.3
	FBRs	2.0	2.5	2.4	47	1.5	1.7	0.7	1.1
	All	2.8	2.7	2.0	2.4	187	188	45	8.2
Average normalized release 1990-1994 and 1995-1997 [GBq (GW a)$^{-1}$]	PWRs			0.18				0.13	
	BWRs			178				351	
	HWRs			0.051				0.048	
	GCRs			0.30				0.17	
	LWGRs			14				8.4	
	FBRs			12				1.0	
	All			40				81	

Table 35
Tritium released from reactors in liquid effluents

Country/reactor	*Release (GBq)*							
	1990	*1991*	*1992*	*1993*	*1994*	*1995*	*1996*	*1997*
PWRs								
Armenia [M1]								
Armenia 2								
Belgium [M1]								
Doel 1-4	63 000	38 100	43 900	32 800	32 800	47 000	31 300	38 400
Tihange 1-3	56 400	34 500	34 900	35 200	33 100	41 200	44 700	47 300
Brazil [C7]								
Angra 1	12 200	11 400	49 300	6 560	587	5 130	4 640	19 500
Bulgaria [C6]	Not reported							
Kozloduy 1-6								11 690
China [C8, T2]								
Guangdong 1-2	-	-	-		22 200	10 100	22 100	38 500
Qinshan	-	-	1 690	1 450	6 320	4 820	3 580	2 950
Maanshan 1-2	4 630	6 030	9 140	16 900	20 500	11 700	15 300	6 790
Czech Republic [N2]								
Dukovany 1-4	20 100	18 300	19 300	18 600	15 600	14 500	17 200	14 600
Finland [F1]								
Loviisa 1-2	12 000	14 000	10 000	12 000	11 000	12 000	9 400	12 000
France [E1]								
Belleville 1-2	31 000	39 000	37 000	38 000	22 000	30 000	36 000	33 000
Blayais 1-4	58 000	54 000	39 000	36 000	32 000	46 000	53 000	40 000
Bugey 2-5	42 000	30 000	15 000	46 000	35 000	33 000	33 000	38 000
Cattenom 1-4	35 000	47 000	86 000	66 000	69 000	80 000	72 000	74 000
Chinon B1-B4	62 000	49 000	52 000	33 000	33 000	44 000	44 000	59 000
Chooz-A (Ardennes)	108 000	95 000	26 000	800	1 000	600	1600	100
Chooz B1-B2							200	13 000
Cruas 1-4	51 000	37 000	34 000	46 000	55 000	43 000	50 000	37 000
Dampierre 1-4	52 000	52 000	73 000	50 000	43 000	44 000	44 000	38 000
Fessenheim 1-2	20 000	26 000	16 000	17 000	20 000	21 000	20 000	22 000
Flamanville 1-2	48 000	37 000	34 000	35 000	30 000	31 000	35 000	25 000
Golfech 1-2	500	8 000	9 000	8 400	30 000	27 000	22 000	33 000
Gravelines 1-6	87 000	80 000	70 000	43 000	60 000	39 000	51 000	58 000
Nogent 1-2	23 000	18 000	18 000	26 000	22 000	25 000	32 000	22 000
Paluel 1-4	100 000	82 000	73 000	77 000	67 000	75 000	70 000	81 000
Penly 1-2	4 000	16 000	20 000	33 000	23 000	24 000	29 000	24 000
St. Alban 1-2	30 000	24 000	9 000	13 000	16 000	22 000	43 000	23 000
St. Laurent B1-B2	34 000	36 000	41 000	33 000	24 000	16 000	20 000	17 000
Tricastin 1-4	49 000	33 000	32 000	34 000	38 000	25 000	46 000	32 000
Germany [B3]								
Biblis A-B	23 000	18 300	25 000	30 000	26 000	21 000	15 000	25 000
Brokdorf	9 400	15 000	19 000	14 000	14 000	12 000	14 000	17 000
Emsland	8 700	8 300	13 000	9 500	13 000	10 000	12 000	15 000
Grafenrheinfeld	12 000	14 000	14 000	13 000	13 000	13 000	16 000	16 000
Greifswald	6 400	200	83	31	69	45	26	24
Grohnde	14 000	16 000	14 000	15 000	18 000	12 000	10 000	7 400
Isar 2	7 200	8 600	16 000	19 000	22 000	19 000	20 000	17 000
Mülheim-Kärlich	2 000	490	420	460	320	250	49	180
Neckarwestheim 1-2	27 000	32 000	24 000	30 000	38 000	35 000	34 000	33 000
Obrigheim	3 500	890	3 300	5 400	4 400	4 600	5 700	5 100
Philippsburg 2	19 000	17 000	15 000	13 000	13 000	17 000	15 000	16 000
Stade	3 400	2 900	4 800	4 800	3 600	2 700	2 900	2 700
Unterweser	11 000	11 000	9 000	8 500	7 700	6 000	12 000	15 000
Hungary [F2]								
Paks 1-4	14 000	16 000	16 000	18 000	18 000	20 000	20 000	15 600

Table 35 (continued)

Country/reactor	*Release (GBq)*							
	1990	*1991*	*1992*	*1993*	*1994*	*1995*	*1996*	*1997*
Japan [J1, J5]								
Genkai 1-4	34 000	26 000	24 000	36 000	50 000	58 000	46 000	61 000
Ikata 1-3	33 000	29 000	25 000	33 000	38 000	53 000	40 000	45 000
Mihama 1-3	20 000	13 000	12 000	18 000	11 000	17 000	17 000	16 000
Ohi 1-4	16 000	20 000	29 000	42 000	63 000	61 000	59 000	46 000
Sendai 1-2	37 000	36 000	48 000	39 000	31 000	42 000	50 000	36 000
Takahama 1-4	35 000	30 000	55 000	69 000	33 000	37 000	57 000	64 000
Tomari 1-2	16 000	11 000	21 000	24 000	21 000	19 000	26 000	30 000
Tsuruga 2	23 000	30 000	7 500	16 000	12 000	18 000	14 000	21 000
Netherlands [N7]								
Borssele	5 540	2 900	4 370	5 980	5 870	6 161	6 020	4 330
Republic of Korea [K1]								
Kori 1-4	76 100	85 900	48 700	66 100	58 000	31 800	32 900	36 700
Ulchin 1-2	13 100	14 300	35 300	29 900	28 000	21 300	20 800	21 900
Yonggwang 1-4	42 600	29 600	28 600	46 600	26 000	27 900	42 200	55 800
Russian Federation								
Balakovo 1-4								
Kalinin 1-2	Average normalized release estimated to be 30,000 GBq (GW a) $^{-1}$							
Kola 1-4								
Novovoronezh 2-5								
Slovakia [N2, S4]								
Bohunice 1-4	13 000	15 600	12 800	14 000	12 600	12 400	12 700	9 580
Slovenia [S1]								
Krsko	13 500	13 500	14 600	10 900	10 500	8 500	9 300	7 800
South Africa [C11]								
Koeberg 1-2	60 700	91 000	83 700	13 500	17 900	11 300	31 800	17 200
Spain [C2]								
Almaraz 1-2	47 200	48 600	53 700	70 600	51 300	42 800	49 300	54 100
Asco 1-2	42 300	53 400	59 300	55 500	35 800	85 800	50 700	58 000
José Cabrera 1	1 740	1 340	2 940	943	511	1 020	2 590	2 160
Trillo 1	10 900	20 000	11 900	19 800	19 000	14 000	19 400	28 800
Vandellos 2	14 600	17 200	10 400	15 700	14 700	13 400	16 600	20 700
Sweden [N3]								
Ringhals	48 800	45 400	53 100	43 400	34 300	21 000	24 600	22 500
Switzerland [F3]								
Beznau 1-2	9 300	8 900	7 200	12 000	11 000	12 000	12 000	12 000
Gösgen	11 000	12 000	12 000	13 000	11 000	14 000	13 000	14 000
Ukraine [G3]								
Khmelnitski 1				1 600	2 050	1 810	663	1 380
Rovno 1-3								
South Ukraine 1-3	15	13	12	25	28	28	39	23
Zaporozhe 1-5								
United Kingdom [M7]								
Sizewell B	-	-	-	-	-	-	37 600	44 200
United States [T3]								
Arkansas One 1-2	29 600	53 900	29 700	28 100	35 400	34 100	42 400	26 500
Beaver Valley 1-2	18 200	17 900	17 200	20 500	13 600	19 200	72 900	20 100
Braidwood 1-2	48 100	25 400	70 900	59 600	45 700	69 600		
Byron 1-2	36 900	52 900	58 500	76 200		50 000	52 100	
Callaway 1	37 700	45 400	21 900	52 000	38 100	29 300	43 300	25 300
Calvert Cliffs 1-2	2 700	37 600	65 600	23 500	24 200	28 200	28 000	33 600
Catawba 1-2	22 000	23 900	28 600	30 600	21 700	18 100	23 700	23 900
Comanche Peak 1-2	6 920	17 000	22 600	18 600	32 900	31 100	36 500	53 800
Crystal River 3	18 900	16 600	13 500	21 800	12 200		9 700	
Davis-Besse 1	4 700	12 100	14 100	6 700	16 400	6 200	19 400	25 100
Diablo Canyon 1-2	35 800	38 900	45 100	38 100	102 000	58 090	35 500	49 600
Donald Cook 1-2	57 700	57 400	16 000	22 200	212	300	75 200	111 000

Table 35 (continued)

Country/reactor	*Release (GBq)*							
	1990	*1991*	*1992*	*1993*	*1994*	*1995*	*1996*	*1997*
United States *(continued)*								
Farley 1-2	52 100	30 500	59 500	67 300	50 100	46 700	56 400	35 800
Fort Calhoun 1	6 440	6 500	3 920	8 840	8 820	9 500	18 100	
R. E. Ginna	11 900	13 900	7 880	6 550	5 100	3 610	4 400	
Haddam Neck	36 600	171 000	31 900	148 000				
Harris 1	26 900	10 800	33 400	20 500	37 400	11 800	16 900	11 000
Indian Point 1-3	36 100	40 100	42 400	21 600				
Kewaunee	14 000	16 100	10 700	8 730	6 070	8 730	11 600	15
Maine Yankee	8 990	14 400	8 030	10 100	14 600	1 650	11 000	4 710
McGuire 1-2	33 900	32 500	32 000	28 700	17 800	23 900	23 800	21 800
Millstone 2-3	48 100	21 100	26 000	31 300	37 700	31 600	14 800	10 700
North Anna 1-2	61 900	42 900	34 400	25 600	45 800	36 100	41 500	37 300
Oconee 1-2-3	36 700	41 800	36 900	40 700	33 600	30 900	32 500	22 900
Palisades	5 510	2 040	29 90	7 770	674	4 660	7 590	5 100
Palo Verde 1-3	0	0	0	0				
Point Beach 1-2	32 300	29 100	15 400	17 200	17 200	19 600	15 500	6 360
Prairie Island 1-2	14 700	20 600	17 500	17 800	13 800	28 900	23 200	20 900
Rancho Seco 1	507	36.4	895	275				
H. B. Robinson 2	13 100	6 960	14 600	31 300	7 990	36 700	36 600	33 300
Salem 1-2	24 300	38 800	17 400	33 300	40 600	14 300	1 720	2 320
San Onofre 1-3	87 000	86 300	144 000	52 700	33 000	36 200	53 700	11 400
Seabrook 1	4 180	14 280	18 500	20 800				
Sequoyah 1-2	31 600	61 100	53 300	20 700	18 200		46 700	
South Texas 1-2	30 200	40 300	50 400	8 360	27 900	137 000	59 800	60 600
St. Lucie 1-2	21 000	30 000	29 600	18 800	19 200	27 800		
Surry 1-2	41 000	33 800	36 000	48 700	36 200	30 800	36 700	41 100
Three Mile Island 1	7 810	13 300	20 700	13 900	13 200	19 500	6 180	27 600
Trojan	8 100	6 250	7 250	45 100	336	106	138	150
Turkey Point 3-4	23 800	7 550	16 400	19 000	27 800	11 700		
Virgil C. Summer 1	15 600	30 100	22 500	17 700	27 800	11 300	21 400	34 100
Vogtle 1-2	43 400	40 500	54 800	28 200	38 900	35 800	60 500	54 400
Waterford 3	26 300	12 700	18 300	18 100	24 700	43 700	19 200	12 500
Watts Bar	-	-	-	-			8 260	
Wolf Creek	21 800	26 500	16 700	37 000			20 000	
Yankee NPS	7 110	7 510	2 330	18.5	22.6	7.03	5.42	2.96
Zion 1-2	25 200	34 400	19 300	45 900	25 100	46 300	46 800	8 550
BWRs								
China [T2]								
Chin Shan 1-2	1 890	1 390	1 530	1 090	973	1 260	1 480	350
Kuosheng 1-2	1 020	2 670	3 960	2 800	4 850	729	367	160
Finland [F1]								
Olkiluoto 1-2	1 300	1 900	1 800	3 600	2 800	1 500	2 400	1 300
Germany [B3]								
Brunsbüttel	170	290	240	74	23	120	350	240
Gundremmingen B,C	2 200	3 000	2 800	4 800	4 500	6 400	11 000	13 000
Isar 1	460	400	460	640	1 100	1 300	1 000	1 200
Krümmel	960	950	650	610	130	580	680	470
Philippsburg 1	460	630	620	760	470	570	540	490
Würgassen	330	460	410	440	330	35	38	14
India								
Tarapur 1-2								
Japan [J1, J5]								
Fukushima Daiichi 1-6	2 700	2 400	2 100	1 900	1 400	1 100	1 100	1 400
Fukushima Daini 1-4	1 100	870	460	580	580	490	570	1 000
Hamaoka 1-4	2 100	1 300	1 000	1 400	1 300	1 000	680	600
Kashiwazaki Kariwa 1-7	150	42	390	160	160	130	170	80
Onagawa 1-2	68	58	38	90	15	8.5	21	44
Shika 1	-	-	3	16	57	140	170	200
Shimane 1-2	430	510	430	570	1 000	730	1 200	720
Tokai 2	980	1 600	1 400	1 300	830	1 500	1 700	1 200
Tsuruga 1	160	470	380	210	97	110	170	190

Table 35 (continued)

Country/reactor	*Release (GBq)*							
	1990	*1991*	*1992*	*1993*	*1994*	*1995*	*1996*	*1997*
Mexico [C5]								
Laguna Verde 1-2	498	82	158	0.00005	1 970	1 960	531	781
Netherlands [N7]								
Dodewaard	147	152	245	163	90	26	19	18
Spain [C2]								
Confrentes	64.7	235	310	516	385	99.4	160	511
S. Maria de Garona	157	73.7	427	177	371	121	165	231
Sweden [N3]								
Barsebeck 1-2	1 100	1 000	1 500	580	530	554	1 100	760
Forsmark 1-3	1 900	3 500	2 600	2 920	2 370	2 340	1 990	2 000
Oskarshamn 1-3	2 600	2 500	1 700	740	1 130	1 190	1 380	1 360
Ringhals 1	711	882	1 270	500	860	832	790	490
Switzerland [F3]								
Leibstadt	930	810	950	620	570	470	710	1 100
Mühleberg	330	380	200	300	200	340	290	320
United States [T3]								
Big Rock Point	21.8	9.29	40.0	5.85	1.55	3.99	8.79	5.03
Browns Ferry 1-3	7.66	221	1 050	459	1 630			
Brunswick 1-2	1 830	2 960	1 570	1 750	2 580	2 040	1 750	962
Clinton 1	96.2	165	87.3	0	0	0	0	0
Cooper	188	335	541	400	129	2 780	198	218
Dresden 2-3	755	474	158	862	551	96.1	425	462
Duane Arnold 1	-	-	-	0	0	0	0	0
Enrico Fermi 2	27.6	74.7	13.0	13.8	90.0	0	0	0
Fitzpatrick	114	282	105	53.3	23.9	13.5	168	0
Grand Gulf 1	699	799	851	2 330	5 980	4 850	7 990	6 360
Hatch 1-2	836	1 080	1 650	1 880	1 700	1 700	1 180	890
Hope Creek 1	437	907	4 630	2 280	6 070	1 710	418	457
Lasalle 1-2	13.8	0	0.0011	0	5.37	0		
Limerick 1-2	1 120	507	389	951	2 100	1 650		
Millstone 1	749	311	272	907	747	485	271	30
Monticello	0	0	0	0.0007	0	0	0	0
Nine Mile Point 1-2	229	288	331	877	654	707		
Oyster Creek	-	22.3	-	0	0	-	226	0.37
Peach Bottom 2-3	870	540	655	267	95.2	1 480	3 420	
Perry 1	325	392	343	346	343			
Pilgrim 1	136	377	0.54	139	34.7	650	542	875
Quad Cities 1-2	966	164	463	1 360	1 740	834	818	1 040
River Bend 1	3 090	1 130	866	1 120	2 400	758	202	296
Susquehanna 1-2	2 150	1 710	2 850	2 510	3 760	2 940	1 240	1 280
Vermont Yankee	0	0	0.0015	0	0	0	0	0
WPPSS 2	27.9	67.0	400	1 260	307	192	152	
HWRs								
Argentina [C3]								
Atucha 1	530 000	550 000	770 000	920 000	2 200 000	500 000	550 000	1 200 000
Embalse	220 000	520 000	160 000	200 000	140 000	230 000	320 000	160 000
Canada [A2]								
Bruce 1-4	1 221 000	3 241 000	1 700 000	1 480 000	1 440 000	1 900 000	1 200 000	310 000
Bruce 5-8	481 000	488 000	410 000	658 000	555 000	380 000	230 000	680 000
Darlington 1-4	12 600	71 000	46 000	57 700	130 000	140 000	120 000	112 000
Gentilly 2	163 000	248 000	263 000	241 000	134 000	200 000	120 000	140 000
Pickering 1-4	407 000	395 000	3 034 000	518 000	555 000	440 000	430 000	350 000
Pickering 5-8	30 000	32 000	44 000	12 600	118 000	110 000	160 000	50 000
Point Lepreau	160 000	110 000	320 000	470 000	260 000	170 000	480 000	500 000
India [B4]								
Kakrapar 1-2	-	-	-					
Kalpakkam 1-2	142 800	211 500	366 000	428 600	266 400			
Narora 1-2	9 950	15 380	34 200	58 680	49 020			
Rajasthan 1-2	23 690	31 170	30 190	65 450	19 010			

Table 35 (continued)

Country/reactor	*Release (GBq)*							
	1990	*1991*	*1992*	*1993*	*1994*	*1995*	*1996*	*1997*
Japan [J1, J5]								
Fugen	3 100	1 600	3 400	3 200	4 200	3 800	5 500	5 100
Pakistan [P2]								
Karachi	127 000	94 300	46 300	56 200	118 000	168 000	105 000	39 100
Republic of Korea [K1]								
Wolsong 1-2	51 800	93 200	42 000	46 300	180 000	170 000	50 000	94 700
Romania								
Cernavoda	-	-	-	-	-	-	8 210	11 600
United Kingdom [M7, N5]								
Winfrith	39 330	13 280	13 790	74 010	59 980		1 610	3 900
GCRs								
France [E1]								
Bugey 1	0	0	0	0	9 600	100	2 800	8 200
Chinon A2-3	2 000	0	0	0	0	0	0	0
St. Laurent A1-2	-	-	-	-	-	-	-	-
Japan [J1, J5]								
Tokai 1	0.037	1.4	0.83	24	5.1	9.2	16	20
Spain [C2]								
Vandellos 1	141	74.3	18 300	105	114	45.6	206	
U. K. [M7, N4, N5]								
Berkeley	1 350	272	157	265	29.1	39.5	37.2	55.2
Bradwell	1 380	1 370	3 920	3 030	2 170	2 080	1 360	1 460
Calder Hall	-	-	-					
Chapelcross	280	1 870	690	500	490	500	368	198
Dungeness A	713	492	451	4 430	547	296	1 380	135
Dungeness B1-B2	7 200	76 100	93 300	268 900	236 200	15 080	252 000	247 000
Hartlepool A1-A2	166 100	140 900	276 900	349 800	289 400	239 000	353 000	367 000
Heysham 1A-B, 2A-B	202 100	416 000	525 000	854 700	732 600	584 800	710 000	816 000
Hinkley Point A	913	780	706	779	713	757	670	810
Hinkley Point B, A-B	295 600	277 000	317 000	390 000	336 000	431 000	319 000	385 000
Hunterston A1	520	250	170	360	200	41.0	22.9	9.9
Hunterston B1-B2	353 000	257 000	245 000	362 000	423 000	449 000	399 000	413 000
Oldbury A	1 750	271	215	229	263	233	186	178
Sizewell A	5 010	5 610	5 080	2 790	3 570	17 400	1 130	5 060
Torness A-B	82 000	132 000	250 000	235 000	220 000	270 000	298 000	324 000
Trawsfynydd	2 520	360	222	74.7	122	232	103	298
Wylfa	5 380	5 680	2 750	5 920	6 980	7 560	9 880	7 020
LWGRs								
Lithuania								
Ignalina 1-2								
Russian Federation [M6]								
Bilibino 1-4	Only average normalized release reported							
Kursk 1-4								
Leningrad 1-4								
Smolensk 1-3								
Ukraine [G3]								
Chernobyl 1-3	Only average normalized release reported							
FBRs								
France [E1]								
Creys-Malville	70	20	10	1	22	28	630	1
Phenix								
Kazakhstan								
Bn-350								

Table 35 (continued)

Country/reactor	*Release (GBq)*							
	1990	*1991*	*1992*	*1993*	*1994*	*1995*	*1996*	*1997*
Russian Federation Beloyarsky 3								
United Kingdom Dounreay PFR								

Summary parameter	*Reactor*	*Release (TBq)*							
		1990	*1991*	*1992*	*1993*	*1994*	*1995*	*1996*	*1997*
All reactors									
Total release (TBq)	PWRs	2 935	3 084	2 995	2 954	2 560	2 677	2 814	2 551
	BWRs	39.6	41.4	45.3	47.3	60.0	48.5	49.8	43.1
	HWRs	3 622	6 115	7 283	5 290	6 225	4 412	3 780	3 656
	GCRs	1 128	1 316	1 740	2 479	2 262	2 018	2 349	2 575
	LWGRs	0	0	0	0	0	0	0	0
	FBRs	0.070	0.020	0.010	0.001	0.022	0.028	0.63	0.001
	All	7 725	10 560	12 060	10 770	11 110	9 155	8 994	8 814
Annual normalized release [TBq (GW a)$^{-1}$]	PWRs	23	24	22	21	18	19	19	18
	BWRs	0.85	0.81	0.95	0.93	1.14	0.85	0.95	0.82
	HWRs	367	536	682	426	452	361	321	316
	GCRs	163	183	215	271	247	236	314	284
	LWGRs	-	-	-	-	-	-	-	-
	FBRs	1.0	-	-	-	26	-	1.6	-
	All	41	53	60	51	52	42	41	41
Average normalized release 1990-1994 and 1995-1997 [TBq (GW a)$^{-1}$]	PWRs	22					19		
	BWRs	0.94					0.87		
	HWRs	490					330		
	GCRs	220					280		
	LWGRs	-					-		
	FBRs	1.8					1.7		
	All	51					41		

Table 36
Other radionuclides released from reactors in liquid effluents

Country/reactor	*Release (GBq)*							
	1990	*1991*	*1992*	*1993*	*1994*	*1995*	*1996*	*1997*
PWRs								
Armenia [A5]								
Armenia 2							22.9	15.4
Belgium [M1]								
Doel 1-4	15.5	22.3	4.4	23.6	8.6	37.8	18.9	26.4
Tihange 1-3	41.5	43.7	53.6	40.9	23.8	22.5	52.3	24.3
Brazil [C7]								
Angra 1	0.430	0.197	0.167	0.548	0.182	0.214	0.19	1.08
Bulgaria [C6]								
Kozloduy 1-6	2.07	2.46	2.03	2.07	1.63	3.61	2.53	2.38
China [C8, T2]								
Guangdong 1-2	-	-	-		89.2	28.9	9.32	11.3
Qinshan	-	-	0.732	0.650	0.45	0.412	0.500	0.336
Maanshan 1-2	0.313	0.736	2.75	4.11	0.433	0.336	0.168	0.522
Czech Republic [N2]								
Dukovany 1-4	0.19	0.34	0.094	0.41	0.31	0.17	0.095	0.077
Finland [F1]								
Loviisa 1-2	18	5.2	3.5	1.9	0.41	0.073	0.056	0.012
France [E1]								
Belleville 1-2	25	10	11	16	7.9	4.0	6.1	3.3
Blayais 1-4	73	40	25	11	10	14	4.9	2.2
Bugey 2-5	255	104	51	26	18	9.6	12	9.6
Cattenom 1-4	12	13	15	9.0	16	7.0	3.8	2.3
Chinon B1-B4	107	96	20	9.5	7.3	10	10	3.2
Chooz-A (Ardennes)	18	13	10	5.5	7.5	20	4.4	1.8
Chooz B1-B2							0.2	1.9
Cruas 1-4	17	13	9.0	5.9	6.1	3.9	4.4	2.8
Dampierre 1-4	46	20	10	7.6	9.6	9.0	7.0	7.8
Fessenheim 1-2	34	18	13	6.8	5.9	2.2	2.7	6.1
Flamanville 1-2	32	40	11	6.9	7.9	3.4	2.0	2.8
Golfech 1-2	0.28	0.07	0.7	1.1	2.3	4.8	1.7	2.8
Gravelines 1-6	173	73	23	12	9.5	18	14	5.8
Nogent 1-2	28	6.0	3.0	3.0	1.7	3.0	3.0	3.2
Paluel 1-4	180	62	24	9.9	8.5	9.2	4.6	6.5
Penly 1-2	26	2.0	4.0	3.8	3.3	1.8	1.6	1.7
St. Alban 1-2	61	30	6.0	3.4	2.8	3.0	3.0	5.4
St. Laurent B1-B2	23	20	6.0	8.6	5.4	2.3	2.0	3.0
Tricastin 1-4	83	40	24	8.9	6.7	6.4	5.2	8.6
Germany [B3]								
Biblis A-B	0.52	0.56	0.46	0.48	0.83	0.73	0.52	0.34
Brokdorf	0	0	0	0	0	0.11	0.026	0.022
Emsland	0.0087	0.0033	0.00065	0.0006	0.0007	0.00021	0.00001	0
Grafenrheinfeld	0.044	0.047	0.012	0.032	0.017	0.017	0.011	0.03
Greifswald	3.7	0.62	0.32	0.17	0.16	0.038	0.16	0.16
Grohnde	0.03	0.093	0.013	0.04	0.049	0.13	0.11	0.046
Isar 2	0.06	0.0039	0.0095	0.0083	0.0004	-	0.00029	0.012
Mülheim-Kärlich	0.32	0.066	0.24	0.14	0.15	0.036	0.0089	0.0084
Neckarwestheim 1-2	0.091	0.098	0.045	0.021	0.016	0.028	0.104	0.026
Obrigheim	0.23	0.15	0.21	0.11	0.24	0.52	0.36	0.23
Philippsburg 2	0.39	0.18	0.49	0.61	0.92	0.44	0.29	0.43
Stade	0.52	0.49	0.45	0.32	0.049	0.37	0.18	0.13
Unterweser	0.15	0.36	0.21	0.23	0.11	0.16	0.20	0.12
Hungary [F2]								
Paks 1-4	2.03	3.51	2.24	1.82	2.40	1.20	0.81	0.67

Table 36 (continued)

Country/reactor	*Release (GBq)*							
	1990	*1991*	*1992*	*1993*	*1994*	*1995*	*1996*	*1997*
Japan [J1, J5]								
Genkai 1-4	0	0	0	0	0	0	0	0
Ikata 1-3	0	0	0	0	0	0	0	0
Mihama 1-3	0.016	0.0005	0.0030	0.0003	0.0001	0.0005	0	0
Ohi 1-4	0.0007	0	0.00008	0.0001	0	0	0	0
Sendai 1-2	0	0	0	0	0	0	0	0
Takahama 1-4	0	0	0	0	0	0	0	0
Tomari 1-2	0	0	0	0	0	0	0	0
Tsuruga 2	0.0043	0.00004	0	0.0002	0	0.00009	0	0
Netherlands [N7]								
Borssele	1.9	1.3	0.83	0.58	0.73	0.62	0.38	1.3
Republic of Korea [K1]								
Kori 1-4	48.7	0.61	4.94	1.03	1.80	0.86	0.43	0.11
Ulchin 1-2	1.48	1.67	0.54	0.93	1.40	0.57	0.26	0
Yonggwang 1-4	1.18	0.41	0.24	0.13	0.23	0.21	0.22	0.016
Russian Federation [M6]								
Balakovo 1-4	0.17	0.21	0.25	0.13	0.74	0.33	0.19	0.65
Kalinin 1-2	0.25	0.46	1.60	1.68	1.64	1.53	1.46	1.18
Kola 1-4	0.15	0.09	0.17	0.16	0.07	0.01	0.12	0.15
Novovoronezh 2-5	0.16	0.19	0.37	0.34	0.34	0.16	0.10	0.70
Slovakia [N2, S4]								
Bohunice 1-4	0.15	0.97	0.29	0.2	0.14	0.15	0.085	0.078
Slovenia [S1]								
Krsko	1.54	1.53	2.50	2.90	1.60	0.70	7.90	1.20
South Africa [C11]								
Koeberg 1-2	1.56	1.16	2.49	21.3	59.8	59.7	57.5	47.4
Spain [C2]								
Almaraz 1-2	28.7	17.6	12.4	7.87	17.4	24.4	14.4	12.7
Asco 1-2	33.2	33.3	24.68	28.4	31.9	52.1	12.4	19.8
José Cabrera 1	12.6	7.53	4.66	1.69	3.84	0.231	0.194	0.202
Trillo 1	0.74	0.25	0.43	1.05	0.97	0.685	0.761	1.34
Vandellos 2	15.6	8.95	14.6	10	30.9	17.3	11.2	19.3
Sweden [N3]								
Ringhals 2-4	235	75.9	102	91.4	98.1	81.1	48.2	47.3
Switzerland [F3]								
Beznau 1-2	6.2	4.3	12	8.5	3	2.1	3.0	1.8
Gösgen	0.011	0.0014	0.0034	0.13	0.005	0.20	0.20	0.20
Ukraine [G3]								
Khmelnitski 1	0.0096	0.0093	0.0078	0.0071	0.0067	0.0033	0.0062	0.0016
Rovno 1-3	0.48	0.55	0.48	0.99	3.05	8.10	2.61	1.94
South Ukraine 1-3	0.023	0.024	0.018	0.014	0.0067	0.0083	0.01	0.0086
Zaporozhe 1-6			0.13	0.42	0.17	0.81	0.20	0.47
United Kingdom [M7]								
Sizewell B	-	-	-	-	-	-	19.9	21.3
United States [T3]								
Arkansas One 1-2	96.6	142	201	82.4	52.4	82.9	49.1	24.6
Beaver Valley 1-2	94.1	11.6	12.6	14.7	7.62	14.8	41.4	13.7
Braidwood 1-2	158	747	38.7	35.3	38.2	29.7		
Byron 1-2	43.7	24.8	152	46.6		66.8		
Callaway 1	1.43	0.59	0.17	1.48	0.36	0.38	29.5	7.19
Calvert Cliffs 1-2	52.3	58.8	53.1	57.0	38.9	20.6	12.7	17.8
Catawba 1-2	72.4	28.2	34.4	33.1	22.2	23.2	11.4	4.9
Comanche Peak 1-2	0.44	1.80	14.8	15.5	9.2	4.6	5.5	4.2
Crystal River 3	22.9	6.66	60.3	19.6	43.3		23.0	
Davis-Besse 1	5.22	6.81	4.07	1.93	59.9	2.90	91.2	9.94
Diablo Canyon 1-2	104	31.3	27.5	36.4	84.7	40.5	14.3	8.6
Donald Cook 1-2	59.6	38.1	41.4	19.9	2.46	10.9	79.4	49.3

Table 36 (continued)

Country/reactor	*Release (GBq)*							
	1990	*1991*	*1992*	*1993*	*1994*	*1995*	*1996*	*1997*
United States *(continued)*								
Farley 1-2	6.18	17.4	13.9	13.3	11.3	11.0	5.03	7.37
Fort Calhoun 1	29.8	77.0	21.8	19.2	13.3	52.1	114	
R. E. Ginna	5.55	5.62	12.7	5.07	3.38	1.46	4.79	
Haddam Neck	99.5	27.5	6.40	30.9				
Harris 1	27.0	24.5	11.6	2.88	5.9	6.0	2.7	2.4
Indian Point 1-3	50.7	58.7	64.5	30.7				
Kewaunee	7.62	8.70	2.38	4.44	3.32	3.04	2.15	0.58
Maine Yankee	6.92	15.3	9.29	5.99	6.27	9.12	5.91	3.29
McGuire 1-2	148	77.0	24.2	21.1	32.2	2.98	3.52	2.85
Millstone 2-3	416	187	168	127	47.9	61.6	26.5	10.8
North Anna 1-2	25.0	11.8	18.4	17.9	19.8	13.0	24.4	4.6
Oconee 1-2-3	115	51.8	95.5	17.4	13.5	14.4	12.7	12.6
Palisades	0.29	0.42	0.14	0.52	0.52	0.55	0.10	0.40
Palo Verde 1-3	0	0	0	0				
Point Beach 1-2	0.43	2.18	15.9	8.58	5.56	5.59	1.78	8.95
Prairie Island 1-2	4.81	6.85	24.6	7.22	19.5	16.5	20.7	32.3
Rancho Seco 1	0.0077	0.0075	0.018	0.015				
H. B. Robinson 2	13.3	8.73	8.14	2.02	1.97	3.25	2.95	0.99
Salem 1-2	227	209	255	254	185	126	18.4	21.5
San Onofre 1-3	22.4	19.6	17.3	53.0	10.5	12.1	6.9	12.2
Seabrook 1	0.082	4.51	4.40	3.40				
Sequoyah 1-2	45.1	54.8	53.7	56.2	74.1		88.1	
South Texas 1-2	485	370	143	32.1	18.0	32.7	38.9	23.5
St. Lucie 1-2	59.0	26.2	37.9	53.1	120	76.3		
Surry 1-2	170	105	14.6	0.77	2.4	2.1	7.2	15.0
Three Mile Island 1	0.88	1.30	0.96	3.28	1.92	2.55	0.16	0.26
Trojan	5.33	2.15	3.31	3.92	0.48	4.08	1.82	0.73
Turkey Point 3-4	10.4	27.2	22.1	17.6	22.5	2.76		
Virgil C. Summer 1	13.2	22.5	8.25	7.14	17.3	4.23	5.83	2.34
Vogtle 1-2	47.3	11.3	7.12	56.3	28.3	15.0	37.6	21.3
Waterford 3	27.0	33.7	48.5	22.3	389	140	30.2	50.0
Watts Bar	-	-	-	-			1.81	
Wolf Creek	11.7	78.4	10.8	26.1			406	
Yankee NPS	2.20	0.49	0.23	0.027	0.011	0.014	0.016	0.008
Zion 1-2	132	62.2	67.0	38.2	41.6	40.1	33.1	6.22
BWRs								
China [T2]								
Chin Shan 1-2	20.3	6.15	3.39	2.13	2.97	2.29	2.08	2.25
Kuosheng 1-2	9.06	42.2	17.3	8.70	25.8	5.39	2.34	3.52
Finland [F1]								
Olkiluoto 1-2	31	22	17	9.5	11	24	16	9.5
Germany [B3]								
Brunsbüttel	0.17	0.46	0.17	0.088	0.023	0.058	0.11	0.037
Gundremmingen B,C	0.49	0.5	0.51	0.55	0.99	0.48	0.64	1.1
Isar 1	0.28	0.069	0.16	0.25	0.25	0.15	0.16	0.14
Krümmel	0.016	0.015	0.012	0.012	0.009	0.016	0.014	0.0028
Philippsburg 1	0.65	0.25	0.18	0.52	0.42	0.25	0.84	0.92
Würgassen	0.4	0.52	0.61	0.42	1	0.12	0.11	0.098
India [B4]								
Tarapur 1-2	1 430	1 420	1 120	1 210	762			
Japan [J1, J5]								
Fukushima Daiichi 1-6	0	0	0	0	0	0	0	0
Fukushima Daini 1-4	0	0	0	0	0	0	0	0
Hamaoka 1-4	0.0091	0.0052	0.0024	0.0006	0	0	0	0
Kashiwazaki Kariwa 1-7	0	0	0	0	0	0	0	0
Onagawa 1-2	0	0	0	0	0	0	0	0
Shika 1	-	-	0	0	0	0	0	0
Shimane 1-2	0.0006	0.0015	0.0024	0.0022	0.0005	0.00007	0	0
Tokai 2	0	0	0	0	0	0	0	0
Tsuruga 1	0.0013	0.0065	0.0025	0	0	0	0	0

Table 36 (continued)

Country/reactor	*Release (GBq)*							
	1990	*1991*	*1992*	*1993*	*1994*	*1995*	*1996*	*1997*
Mexico [C5]								
Laguna Verde 1-2	18.8	9.5	11.2	5.66	23.5	20.1	1.14	0.88
Netherlands [N7]								
Dodewaard	9.12	9.24	8.35	6.68	8.89	12.9	13.3	5.5
Spain [C2]								
Confrentes	0.1	0.18	0.15	0.13	0.11	0.063	0.119	0.392
S. Maria de Garona	0.57	0.24	3.58	0.58	1.64	0.591	0.765	0.650
Sweden [N3]								
Barsebeck 1-2	45.4	104	105	26.1	26.6	57.8	194	58.3
Forsmark 1-3	230	245	118	156	118	60.5	72.4	115
Oskarshamn 1-3	140	167	129	102	68.3	97.6	130	51.1
Ringhals 1	70.0	54.0	111	118	247	69.5	47.9	155
Switzerland [F3]								
Leibstadt	0.49	0.24	0.17	0.18	0.5	0.4	0.4	0.4
Mühleberg	4.7	2	1.8	3.7	1.9	1.7	2.0	3.7
United States [T3]								
Big Rock Point	1.35	4.51	5.55	3.59	5.30	3.83	8.98	0.90
Browns Ferry 1-3	11.2	31.0	89.2	178	41.5			
Brunswick 1-2	16.9	16.1	1.83	3.85	1.67	15.4	1.48	0.54
Clinton 1	0.92	1.26	0.67	0	0.00004	0	0.00003	0
Cooper	75.4	84.8	147	85.7	12.5	49.3	41.8	48.1
Dresden 2-3	26.3	28.2	0.82	5.99	1.48	2.30	0.98	0.53
Duane Arnold 1	0	0	0	0	0	0	0	0
Enrico Fermi 2	8.07	7.96	0.0056	0.055	0.40	0	0	0
Fitzpatrick	1.01	1.14	0.43	0.070	0.028	0.002	0.33	0
Grand Gulf 1	23.9	32.4	4.44	6.14	8.87	13.1	14.2	4.81
Hatch 1-2	12.6	28.2	34.2	31.3	36.8	14.3	14.5	10.8
Hope Creek 1	55.1	29.2	11.3	13.4	3.32	52.0	28.9	10.1
Lasalle 1-2	0.91	0	0.011	0	0.16	0		
Limerick 1-2	12.7	1.24	1.09	5.37	18.3	16.5		
Millstone 1	5.22	50.3	17.1	4.74	2.20	0.95	1.06	0.88
Monticello	0	0	0	0	0	0	0	0
Nine Mile Point 1-2	2.42	6.22	9.62	4.33	3.96			
Oyster Creek	0.0025	0.89	-	0	0	-	0.10	0
Peach Bottom 2-3	0.50	1.38	0.97	2.09	5.95	1.80	1.25	
Perry 1	22.6	4.37	2.21	5.74	425	1.78	1.45	
Pilgrim 1	0.59	1.48	0.12	0.85	0.10	2.83	0.34	4.89
Quad Cities 1-2	4.18	27.1	1.45	2.27	2.22	2.32	0.93	1.08
River Bend 1	27.3	13.4	61.4	36.0	168	109	16.9	19.6
Susquehanna 1-2	6.29	2.30	1.79	1.82	4.44	21.5	2.07	0.36
Vermont Yankee	0	0	0.001	0	0	0	0	0
WPPSS 2	0.57	1.28	3.51	7.62	1.05	0.96	0.41	
HWRs								
Argentina [C3]								
Atucha 1	130	93	93	60	660	330	680	230
Embalse	3.5	20	2	2	1.6	4.3	4.6	2.0
Canada [A2]								
Bruce 1-4	20	20	30	26.5	44.4	29	20	21
Bruce 5-8	4.0	3.0	5.0	5.15	5.9	9.6	4.5	14.8
Darlington 1-4	330	710	27	11	16	12	20	9.8
Gentilly 2	4.2	3.0	14	9.0	6.9	42	6.5	5.0
Pickering 1-4	52	44	48	34.8	37	17	13	7.3
Pickering 5-8	10	10	2.2	5.55	6.7	6.7	0	5.2
Point Lepreau	2.0	4.0	2.0	5.24	7.3	5.9	3.2	2.7
India [B4]								
Kakrapar 1-2	-	-	-					
Kalpakkam 1-2	26.4	23.6	26.3	35.3	25.5			
Narora 1-2	0.04	0.94	14.5	11.3	3.14			
Rajasthan 1-2	3.63	2.93	2.09	2.40	1.77			

Table 36 (continued)

Country/reactor	*Release (GBq)*							
	1990	*1991*	*1992*	*1993*	*1994*	*1995*	*1996*	*1997*
Japan [J1, J5]								
Fugen	0.014	0.0047	0.011	0.0016	0	0	0	0
Pakistan [P2]								
Karachi	8.5	13.3	13.0	22.2	8.9	5.2	4.8	5.3
Republic of Korea [K1]								
Wolsong 1-2	0.20	0.20	0.30	0.55	0.43	0.17	0	0
Romania								
Cernavoda 1	-	-	-	-	-	-	0.04	7.15
United Kingdom [N5]								
Winfrith	3 994	665	115	55	63		29	
GCRs								
France [E1]								
Bugey 1	0.2	2	1	0.9	3.7	0.6	2.5	6.9
Chinon A2-3	0.9	1	2	1.4	3.3	4.0	0.6	0.4
St. Laurent A1-2	-	-	-	-	-	-	-	-
Japan [J1, J5]								
Tokai 1	0.034	0.016	0.016	0.0067	0.0015	0.0089	0.0064	0.0029
Spain [C2]								
Vandellos 1	8.77	9.29	30.7	17.9	30.4	19.8	58.3	
U. K. [M7, N4, N5]								
Berkeley	329	496	156	378	144	134	49	72
Bradwell	324	453	1 380	603	725	809	756	849
Calder Hall	-	-	-					
Chapelcross	110	110	70	270	310	160	111	40
Dungeness A	395	374	507	1 720	996	802	836	792
Dungeness B1-B2	8.9	10.3	8.0	19	51	27	18	27
Hartlepool A1-A2	20	36	49	52	11	8.1	20	11
Heysham 1A-B, 2A-B	73	34	55	48	53	18	6 910	19.7
Hinkley Point A	751	729	610	686	724	981	570	707
Hinkley Point B, A-B	38	27	16	15	21	17	9.0	15
Hunterston A1	320	280	210	290	210	150	141	165
Hunterston B1-B2	50	40	20	34	31	23	5.9	4.1
Oldbury A	429	372	397	505	394	363	186	273
Sizewell A-B	428	467	383	274	292	411	589	233
Torness A-B	1.8	7.0	15	9.8	1.5	2.3	1.8	3.8
Trawsfynydd	334	259	167	41	24	25	21	10
Wylfa	72	88	44	68	54	53	61	46
LWGRs								
Lithuania [E2]								
Ignalina 1-2	25.8	3.1	22.6	4.2	7.7	16.6	5.9	6.1
Russian Federation [M6]								
Bilibino 1-4	0.10	0.10	0.11	0.06	0.07	0.06	0.08	0.04
Kursk 1-4	0.03	0.0004	0.002	0.001	0.007	0.03	0.007	0.004
Leningrad 1-4	0.003	0.0004	0.003	0.003	0.008	0.001	0.003	0.003
Smolensk 1-3	0.09	0.08	0.04	0.02	0.03	0.02	0.03	0.03
Ukraine [G3]								
Chernobyl 1-3	61.8	36.3	24.8	17.0	18.9	28.1	45.1	40.0
FBRs								
France [E1]								
Creys-Malville	0.10	0.11	0.083	0.013	0.017	0.010	0.021	0.017
Phenix								
Kazakhstan [A6]								
Bn-350	22.6	21.5	17.4	15.2	14.1	7.8	7.4	7.4

Table 36 (continued)

Country/reactor	*Release (GBq)*							
	1990	*1991*	*1992*	*1993*	*1994*	*1995*	*1996*	*1997*
Russian Federation [M6]								
Beloyarsky 3	3.47	5.46	8.79	3.51	1.89	1.59	1.23	2.67
United Kingdom								
Dounreay PFR								

Summary parameter	*Reactor*	*Release (GBq)*							
		1990	*1991*	*1992*	*1993*	*1994*	*1995*	*1996*	*1997*
All reactors									
Total release (GBq)	PWRs	4 609	3 546	2 356	1 718	1 980	1 454	1 605	685
	BWRs	2 329	2 461	2 040	2 055	2 044	662	620	511
	HWRs	4 588	1 613	394	286	888	462	786	310
	GCRs	3 693	3 794	4 125	5 030	4 079	4 008	10 350	3 275
	LWGRs	87.8	39.6	47.6	21.3	26.7	44.8	51.1	46.2
	FBRs	26.2	27.1	26.3	18.7	16.0	9.4	8.7	10.1
	All	15 330	11 480	8 989	9 130	9 034	6 640	13 420	4 837
Annual normalized release [GBq (GW a)$^{-1}$]	PWRs	34	25	16	11	13	10	10	4.5
	BWRs	48	47	41	40	39	12	12	10
	HWRs	465	141	37	23	65	38	67	27
	GCRs	533	526	511	550	445	470	1 380	361
	LWGRs	8.2	3.8	5.4	2.2	3.5	5.6	5.8	5.9
	FBRs	61	70	50	38	33	24	22	23
	All	72	51	39	39	39	28	56	21
Average normalized release 1990-1994 and 1995-1997 [GBq (GW a)$^{-1}$]	PWRs			19				8.1	
	BWRs			43				11	
	HWRs			130				44	
	GCRs			510				700	
	LWGRs			4.8				5.8	
	FBRs			49				23	
	All			48				35	

Table 37
Normalized releases of radionuclides from nuclear reactors

Release	*Year*	*Normalized release [TBq (GW a)$^{-1}$]*						
		PWR	*BWR*	*GCR*	*HWR*	*LWGR*	*FBR*	*Total* [a]
Noble gases	1970-1974	530	44 000	580	4 800	5 000 [b]	150 [b]	13 000
	1975-1979	430	8 800	3 200	460	5 000 [b]	150 [b]	3 300
	1980-1984	220	2 200	2 300	210	5 500	150 [b]	1 200
	1985-1989	81	290	2 100	170	2 000	820	330
	1990-1994	27	350	1 600	2 100	1 700	380	330
	1995-1997	13	180	1 200	250	460	210	130
Tritium	1970-1974	5.4	1.8	9.9	680	26 [b]	96 [b]	48
	1975-1979	7.8	3.4	7.6 [b]	540	26 [b]	96 [b]	38
	1980-1984	5.9	3.4	5.4	670	26 [b]	96 [b]	44
	1985-1989	2.7	2.1	8.1	690	26 [b]	44	40
	1990-1994	2.3	0.94	4.7	650	26 [b]	49	36
	1995-1997	2.4	0.86	3.9	330	26	49 [b]	16
Carbon-14	1970-1974	0.22 [b]	0.52 [b]	0.22 [b]	6.3 [b]	1.3 [b]	0.12 [b]	0.71
	1975-1979	0.22	0.52 [c]	0.22 [b]	6.3 [b]	1.3 [b]	0.12 [b]	0.70
	1980-1984	0.35	0.33	0.35 [b]	6.3	1.3 [b]	0.12 [b]	0.74
	1985-1989	0.12	0.45	0.54	4.8	1.3	0.12 [b]	0.53
	1990-1994	0.22	0.51	1.4	1.6	1.3 [b]	0.12 [b]	0.44
Iodine-131	1970-1974	0.0033	0.15	0.0014 [b]	0.0014	0.080 [b]	0.0033 [b]	0.047
	1975-1979	0.0050	0.41	0.0014 [b]	0.0031	0.080 [b]	0.0050 [b]	0.12
	1980-1984	0.0018	0.093	0.0014	0.0002	0.080	0.0018 [b]	0.030
	1985-1989	0.0009	0.0018	0.0014	0.0002	0.014	0.0009 [b]	0.002
	1990-1994	0.0003	0.0008	0.0014	0.0004	0.007	0.0003 [b]	0.0007
	1995-1997	0.0002	0.0003	0.0004	0.0001	0.007	0.0002	0.0004
Particulates	1970-1974	0.018 [c]	0.040 [c]	0.0010 [b]	0.00004 [b]	0.015 [b]	0.0002 [b]	0.019
	1975-1979	0.0022	0.053	0.0010	0.00004	0.015 [b]	0.0002 [b]	0.017
	1980-1984	0.0045	0.043	0.0014	0.00004	0.016	0.0002 [b]	0.014
	1985-1989	0.0020	0.0091	0.0007	0.0002	0.012	0.0002	0.004
	1990-1994	0.0002	0.18	0.0003	0.00005	0.014	0.012	0.040
	1995-1997	0.0001	0.35	0.0002	0.00005	0.008	0.001	0.085
Tritium (liquid)	1970-1974	11	3.9	9.9	180	11 [b]	2.9 [b]	19
	1975-1979	38	1.4	25	350	11 [b]	2.9 [b]	42
	1980-1984	27	2.1	96	290	11 [b]	2.9 [b]	38
	1985-1989	25	0.78	120	380	11 [b]	0.4	41
	1990-1994	22	0.94	220	490	11 [b]	1.8	48
	1995-1997	19	0.87	280	340	11 [b]	1.7	38
Other (liquid)	1970-1974	0.20 [b]	2.0 [c]	5.5 [c]	0.60	0.20 [b]	0.20 [b]	2.1
	1975-1979	0.18	0.29	4.8	0.47	0.18 [b]	0.18 [b]	0.70
	1980-1984	0.13	0.12	4.5	0.026	0.13 [b]	0.13 [b]	0.38
	1985-1989	0.056	0.036	1.2	0.030	0.045 [b]	0.004	0.095
	1990-1994	0.019	0.043	0.51	0.13	0.005	0.049	0.047
	1995-1997	0.008	0.011	0.70	0.044	0.006	0.023	0.040

a Weighted by the fraction of energy generated by the reactor types.
b Estimated value.
c Data available for one year only.

Table 38
Collective effective dose per unit release of radionuclides from reactors

Type of release	*Radionuclide*	*Pathway*	*Collective dose per unit release* [a] *(man Sv PBq^{-1})*
Airborne	Noble gases		
	PWR	Immersion	0.11 [b c] (0.12)
	BWR	Immersion	0.43 (0.26)
	GCR	Immersion	0.90 (0.011)
	Tritium	Ingestion	2.1 (11)
	Carbon-14	Ingestion	270 [d] (1 800)
	Iodine [e]	External	4.5
		Ingestion	250
		Inhalation	49
		All pathways	300 (340-510)
	Particulates	External	1 080
		Ingestion	830
		Inhalation	33
		All pathways	2 000 (5 400)
Liquid	Tritium	Ingestion	0.65 (0.81)
	Particulates	Ingestion	330 (20-170)

a Previously assessed values [U3] indicated in parentheses unless unchanged.
b Also assumed for LWGRs and FBRs.
c Also assumed for HWRs.
d Local and regional.
e Expressed in terms of ^{131}I.

Table 39
Normalized collective effective doses from radionuclides released from reactors, 1990-1994

Reactor type	*Electrical energy generated (%)*	*Collective effective dose per unit electrical energy generated [man Sv (GW a)$^{-1}$]*						
		Airborne effluents					*Liquid effluents*	
		Noble gases	*^{3}H*	*^{14}C* [a]	*^{131}I*	*Particulates*	*^{3}H*	*Other*
PWR	65.04	0.003	0.005	0.059	0.0001	0.0004	0.014	0.006
BWR	21.95	0.15	0.002	0.14	0.0002	0.36	0.0006	0.014
GCR	3.65	1.44	0.010	0.38	0.0004	0.0006	0.14	0.17
HWR	5.04	0.23	1.4	0.43	0.0001	0.0001	0.32	0.043
LWGR	4.09	0.19	0.05	0.35	0.002	0.028	0.007	0.002
FBR	0.24	0.042	0.10	0.032	0.00009	0.024	0.0012	0.016
Weighted average		0.11	0.075	0.12	0.0002	0.080	0.031	0.016
Total		0.43						

a Local and regional components only.

Table 40
Radionuclides released from fuel reprocessing plants

Year	Fuel reprocessed (GW a)	Release in airborne effluents (TBq)						Release in liquid effluents (TBq)					
		^{3}H	^{14}C	^{85}Kr	^{129}I	^{131}I	^{137}Cs	^{3}H	^{14}C	^{90}Sr	^{106}Ru	^{129}I	^{137}Cs
France (Cap de La Hague) [C4]													
1970				2 300		0.00026		61		2	100		89
1971		0.9		4 400		0.0074	0.00081	78		8.3	143		243
1972		3.1		8 900		0.1		84		16	140		33
1973		2.6		8 500		0.026		110		19	132		69
1974		7.1		27 000		0.019	<0.00001	281		52	269		56
1975		3.3		24 000		0.067		411		37.6	415		34
1976		1.8		13 000	0.00021	0.011		264		20	278		35
1977	1.4	2.3		25 000	0.0022	0.00007	<0.00001	331		36.4	270		51
1978	1.6	4.4		29 000	0.01	0.0001	<0.00001	729		70	401		39
1979	2.9	7.1		24 000	0.0074	0.028		539		56	374		23
1980	2.8	9.2		30 000	0.017	0.00033	<0.00001	539		29.4	387		27
1981	3.3	10		36 000	0.0098	0.00031	<0.00001	710		27.1	331		39
1982	3.7	6.3		51 000	0.015	0.00018		810		86.3	469		51
1983	5.2	8.3		50 000	0.021	0.0005	<0.00001	1 170		141.8	337	0.1	23
1984	4.8	8.5		27 000	0.027	0.00051	<0.00001	1 460		109.6	351	0.1	30
1985	9.3	33		71 000	0.021	0.00057	0.00008	2 600		47	437	0.13	29
1986	7.2	6.1		29 000	0.011	0.00041	<0.00001	2 310		68.5	403	0.13	10
1987	9.1	15		35 000	0.014	0.00054	<0.00001	2 960		57	525		7.6
1988	7.1	21		27 000	0.021	0.00059		2 540		39.5	259	0.20	8.5
1989	10.8	25		42 000	0.027	0.00077	<0.00001	3 720		28.5	275	0.26	13
1990	12.3	25	2.6	63 000	0.018	0.00053	<0.00001	3 260		15.8	150	0.33	13
1991	18.5	28	2.3	100 000	0.023	0.00074	<0.00001	4 710		29.8	18	0.46	5.6
1992	16.4	30	2	95 000	0.011	0.00038	<0.00001	3 770		17.5	11	0.48	3.0
1993	21.5	42	3.8	120 000	0.010	0.00058	<0.00001	5 150		24.6	8	0.65	4.4
1994	34.3	55	5.4	180 000	0.021	0.00049	<0.00001	8 090		15.6	14	1.1	11
1995	43.4	84	8.5	230 000	0.032	0.00078	<0.00001	9 610		29.6	15.2	1.5	4.6
1996	43.0	75	12	260 000	0.038	0.0015	<0.00001	10 500	9.94	10.6	16.9	1.7	2.4
1997	49.8 [a]	76	17	300 000	0.017	0.0012	<0.00001	11 900	9.65	3.7	19.6	1.6	2.5
Japan (Tokai) [J1, J5]													
1977	0.04	0.25		810	0.00016	0		4.8		0.00014	0	0	0.00093
1978	0.11	0.93		1 800	0.00081	0		30		0.00004	0.0044	0.0011	0.0010
1979	0.18	0.85		1 800	0.00032	0		59		0.00009	0.0025	0.0018	0.00028
1980	0.61	3.5		7 400	0.0007	0		160		0.00002	0.00044	0.00017	0.00022
1981	0.60	3.6		7 800	0.00041	0		140		0	0.00033	0.00004	0.00017
1982	0.54	4.1		7 800	0.00056	0		200		0.00001	0.00023	0.00001	0.00014
1983	0.01	1.5		180	0.00009	0		5.6		<0.00001	0	<0.0001	0.00002
1984	0.12	0.67		1 300	0.00004	0		32		0.00006	0	<0.00001	0
1985	1.2	2.8		10 000	0.001	0		260		<0.00001	0	0.00009	0.00008

Table 40 (continued)

Year	Fuel reprocessed (GW a)	Release in airborne effluents (TBq)						Release in liquid effluents (TBq)					
		^{3}H	^{14}C	^{85}Kr	^{129}I	^{131}I	^{137}Cs	^{3}H	^{14}C	^{90}Sr	^{106}Ru	^{129}I	^{137}Cs
1986	1.2	2.7		13 000	0.0023	0		240		0.00003	0	<0.00001	0.00017
1987	0.93	3.7		12 000	0.00014	0		260		<0.00001	0	<0.00001	0.00015
1988	0.17	2.5		2 700	0.00009	0		74		0	0	0	0.00009
1989	1.1	3.7		9 800	0.00024	0		240		0	0	0.00001	0.00004
1990	1.5	4.2		13 000	0.000024	0	–	360	–	0	0	0.00004	0
1991	1.5	3.2	0.34	15 000	0.00030	0	–	330	–	0	0	0.00003	0.00003
1992	1.5	2.8	0.78	9 800	0.00030	0	–	380	–	0	0	0.00007	0.00007
1993	0.8	2.2	0.31	5 300	0.00024	0	–	160	–	0	0	0.00005	0.00005
1994	1.5	5.4	0.80	18 000	0.00033	0	–	490	–	0	0	0.00007	0.00007
1995	1.0	3.8	0.44	8 600	0.00016	0	–	220	–	0	0	0.00008	0
1996	1.5	3.7	0.48	12 000	0.00016	0	0.001	240	–	0	0	0.00005	0
1997	0	1.5	0.0047	1.6	0	0	–	3.6	–	0	0	0.00001	0
United Kingdom (Sellafield) [B5, J2]													
1970		443	9.0		0.022	0.027	0.066	6 200	1.0	230	1 000	0.10	1 200
1971		443	10.0		0.022	0.069	0.13	1 200	1.0	460	1 400	0.10	1 300
1972	2.6	303	17.3	37 000	0.022	2.4	0.015	1 240	1.0	562	1 130	0.10	1 289
1973		443	24.3		0.022	0.13	0.068	740	1.0	280	1 400	0.10	770
1974		443	17.3		0.022	0.0013	0.038	1 200	1.0	390	1 100	0.10	4 100
1975	3.2	444	20.3	44 000	0.022	0.0011	0.096	1 400	1.0	466	762	0.10	5 230
1976	3.2	444	32.3	44 000	0.024	0.009	0.11	1 200	1.0	381	766	0.13	4 289
1977	2.1	296	26.3	33 000	0.018	0.0078	0.49	910	1.0	427	816	0.096	4 480
1978	1.8	222	8.6	26 000	0.0078	0.045	0.51	1 000	1.0	597	810	0.074	4 090
1979	2.5	290	7.3	35 000	0.017	0.091	0.51	1 200	1.0	250	390	0.12	2 600
1980	2.2	252	8.5	31 000	0.045	0.0033	0.93	1 280	1.0	352	340	0.14	2 970
1981	3.7	459	19.3	52 000	0.027	0.90	0.19	1 966	1.0	277	530	0.19	2 360
1982	3.1	360	9.5	44 000	0.033	0.017	0.054	1 750	1.0	319	420	0.10	2 000
1983	3.0	268	7.3	41 800	0.027	0.015	0.046	1 831	1.0	204	553	0.20	1 200
1984	2.7	349	7.3	37 100	0.030	0.006	0.040	1 586	1.0	72	348	0.10	434
1985	1.7	268	7.3	23 800	0.021	0.006	0.036	1 062	1.3	52	81	0.10	325
1986	3.8	171	5.7	53 300	0.030	0.003	0.038	2 150	2.6	18.3	28	0.12	17.9
1987	2.4	78.3	9.8	34 000	0.019	0.0035	0.0071	1 375	2.1	15	22.1	0.10	11.8
1988	2.8	186	3.6	39 700	0.024	0.0022	0.0038	1 724	3	10.1	23.6	0.13	13.3
1989	3.7	677	4.2	51 700	0.024	0.0021	0.0026	2 144	2	9.2	25	0.17	28.6
1990	3.8	593	4.1	37 600	0.012	0.0012	0.0028	1 699	2.0	4.2	16.5	0.11	23.5
1991	4.5	619	5.8	44 600	0.012	0.0019	0.0036	1 803	2.4	4.1	18.7	0.16	15.6
1992	2.7	324	2.5	27 400	0.019	0.0016	0.0020	1 199	0.8	4.2	12.6	0.07	15.3
1993	5.7	860	11.4	57 000	0.039	0.0020	0.0007	2 309	2.0	17.1	17.1	0.16	21.9
1994	3.8	550	4.2	38 000	0.024	0.0017	0.0007	1 680	8.2	28.9	6.7	0.16	13.8
1995	6.9	580	4.2	97 000	0.020	0.0011	0.0006	2 700	12	28	7.3	0.25	12
1996	7.1	530	3.8	100 000	0.025	0.0023	0.0009	3 000	11	16	9.0	0.41	10
1997	6.8	170	1.8	95 000	0.025	0.0026	0.0006	2 600	4.4	37	9.8	0.52	7.9

a Estimated based on normalized ^{85}Kr release of 6,020 TBq (GW a)$^{-1}$.

Table 41
Normalized releases and collective doses in fuel reprocessing

Year	*Fuel reprocessed (GWa)*	*Normalized release [TBq (GW a)$^{-1}$]*											
		Airborne effluents						*Liquid effluents*					
		^{3}H	^{14}C	^{85}Kr	^{129}I	^{131}I	^{137}Cs	^{3}H	^{14}C	^{90}Sr	^{106}Ru	^{129}I	^{137}Cs
1970-1979	29.2	93	7.3	13 920	0.006	0.12	0.09	399	0.4	131	264	0.04	1 020
1980-1984	36.3	48	3.5	11 690	0.007	0.03	0.04	376	0.3	45	112	0.04	252
1985-1989	62.5	24	2.1	7 263	0.003	0.0003	0.002	378	0.8	7.5	33	0.03	7.4
1990-1994	131	24	0.4	6 300	0.001	0.00009	0.00008	270	0.8	2.0	2.1	0.03	1.0
1995-1997	160	9.6	0.3	6 900	0.001	0.00005	0.00001	255	0.4	0.8	0.5	0.04	0.2

Collective effective dose per unit release (man Sv TBq^{-1})

Year	*Fuel reprocessed (GWa)*	*Airborne effluents*						*Liquid effluents*					
		^{3}H	^{14}C	^{85}Kr	^{129}I	^{131}I	^{137}Cs	^{3}H	^{14}C	^{90}Sr	^{106}Ru	^{129}I	^{137}Cs
		0.0021	0.27	0.0000074	44	0.3	7.4	0.0000014	1.0	0.0047	0.0033	0.099	0.098

Collective effective dose (man Sv) [a]

Year	*Fuel reprocessed (GWa)*	*Airborne effluents*						*Liquid effluents*					
		^{3}H	^{14}C	^{85}Kr	^{129}I	^{131}I	^{137}Cs	^{3}H	^{14}C	^{90}Sr	^{106}Ru	^{129}I	^{137}Cs
Pre-1970	2.3 [b]	0.5	4.5	0.2	0.6	0.08	1.6	0.001	0.9	1.4	2.0	0.009	230
1970-1974	7.0	1.4	14	0.7	1.9	0.25	4.9	0.004	2.7	4.3	6.1	0.03	704
1975-1979	22.2	4.3	44	2.3	5.9	0.79	15	0.01	8.7	14	19	0.09	2 220
1980-1984	36.3	3.7	35	3.1	11	0.28	11	0.02	12	7.6	13	0.1	895
1985-1989	62.5	3.1	36	3.4	9.5	0.006	0.80	0.03	48	2.2	6.9	0.2	46
1990-1994	131	6.6	13	6.1	8.4	0.003	0.08	0.05	98	1.2	0.9	0.4	12
1995-1997	160	3.2	13	8.2	6.9	0.002	0.02	0.06	66	0.6	0.3	0.6	3.9
Total	420	23	158	24	44	1.4	34	0.18	236	31	49	1.4	4 110
		280						4 430					
		4 710											

a Collective doses prior to 1970 and in 1970-1974 and 1975-1979 are estimated using the normalized release estimates of 1970-1979.
b Estimated to be 8% of electrical energy generated.

Table 42
Normalized activity releases of globally dispersed radionuclides from reactors and reprocessing plants

Years	*Normalized release [TBq (GW a)$^{-1}$]*						
	From reactors		*From reprocessing plants*				
	^{3}H	*^{14}C*	*^{3}H*	*^{3}H (to sea)*	*^{14}C*	*^{85}Kr*	*^{129}I*
Pre-1970	67	0.71	93	399	7.7	13 920	0.046
1970-1974	67	0.71	93	399	7.7	13 920	0.046
1975-1979	80	0.70	93	399	7.7	13 920	0.046
1980-1984	83	0.74	48	376	3.9	11 690	0.042
1985-1989	82	0.53	24	378	2.9	7 260	0.029
1990-1994	84	0.44	24	272	1.1	6 330	0.030
1995-1997	54	0.44 [a]	9.6	255	0.7	6 900	0.038

a Estimated value.

Table 43
Activity releases of globally dispersed radionuclides from reactors and reprocessing plants

Years	*Electrical energy generated (GW a)*	*Fuel reprocessed (GW a)*	*Release (TBq)*				
			^{3}H	*^{3}H (to sea)*	*^{14}C*	*^{85}Kr*	*^{129}I*
Pre-1970	28.8	2.30	2 146	919	38	32 060	0.11
1970-1974	87.7	7.04	6 543	2 809	116	97 970	0.32
1975-1979	277	22.2	24 200	8 858	364	308 900	1.01
1980-1984	514	36.3	44 330	13 640	523	424 400	1.53
1985-1989	937	62.5	77 960	23 660	672	454 000	1.79
1990-1994	1 147	130	98 900	35 390	650	823 700	3.87
1995-1997	767	160	42 830	40 770	442	1 102 000	6.14
Total	3 757	420	296 900	126 000	2 805	3 243 000	14.8

Table 44
Collective dose commitment (10,000 years) from globally dispersed radionuclides released from reactors and reprocessing plants

Years	*Collective effective dose (man Sv)* [a] [b]						*Normalized collective effective dose [man Sv (GW a)$^{-1}$]*
	^{3}H	*^{3}H (to sea)*	*^{14}C*	*^{85}Kr*	*^{129}I*	*Total*	
Pre-1970	4.3	0.2	2 670	64	2.1	2 740	95
1970-1974	13	0.6	8 140	196	6.4	8 350	95
1975-1979	48	1.8	25 510	618	20	26 200	95
1980-1984	89	2.7	36 580	849	31	37 550	73
1985-1989	156	4.7	47 070	908	36	48 180	51
1990-1994	198	7.1	45 470	1 650	77	47 400	41
1995-1997	86	8.1	30 930	2 200	123	33 350	43
Total	594	25	196 400	6 490	295	203 800	54

a Collective dose per unit release (man Sv TBq^{-1}): ^{3}H, 0.002; ^{3}H (to sea), 0.0002; ^{14}C: 70; ^{85}Kr, 0.002; ^{129}I, 20.
b Assumes world population at time of release: 5 10^{9} (for ^{3}H and ^{85}Kr); 10^{10} (for ^{14}C and ^{129}I).

Table 45
Normalized collective effective dose to members of the public from radionuclides released in effluents from the nuclear fuel cycle [a]

Source	*Normalized collective effective dose [man Sv (GW a)$^{-1}$]*				
	1970-1979	*1980-1984*	*1985-1989*	*1990-1994*	*1995-1997*
Local and regional component					
Mining	0.19	0.19	0.19	0.19	0.19
Milling	0.008	0.008	0.008	0.008	0.008
Mine and mill tailings (releases over five years)	0.04	0.04	0.04	0.04	0.04
Fuel fabrication	0.003	0.003	0.003	0.003	0.003
Reactor operation					
Atmospheric	2.8	0.7	0.4	0.4	0.4
Aquatic	0.4	0.2	0.06	0.05	0.04
Reprocessing					
Atmospheric	0.3	0.1	0.06	0.03	0.04
Aquatic	8.2	1.8	0.11	0.10	0.09
Transportation	<0.1	<0.1	<0.1	<0.1	<0.1
Total (rounded)	12	3.1	0.97	0.92	0.91
Solid waste disposal and global component					
Mine and mill tailings (releases of radon over 10,000 years)	7.5	7.5	7.5	7.5	7.5
Reactor operation					
Low-level waste disposal	0.00005	0.00005	0.00005	0.00005	0.00005
Intermediate-level waste disposal	0.5	0.5	0.5	0.5	0.5
Reprocessing solid waste disposal	0.05	0.05	0.05	0.05	0.05
Globally dispersed radionuclides (truncated to 10,000 years)	95	70	50	40	40
Total (rounded)	100	80	60	50	50

a Analysis is based on reported releases per unit electrical energy generated and presently adopted dose coefficients. These results may, therefore, differ somewhat from earlier evaluations by the Committee.

Table 46
Local and regional component of the collective effective dose to members of the public from radionuclides released in effluents from the nuclear fuel cycle

Years	*Electrical energy generated (GW a)*	*Normalized collective effective dose [man Sv (GW a)$^{-1}$]*			*Collective effective dose (man Sv)*		
		Mining, milling, fuel fabrication, transportation	*Reactor operation*	*Fuel reprocessing*	*Mining, milling, fuel fabrication, transportation*	*Reactor operation*	*Fuel reprocessing*
Pre-1970	28.8	0.24	3.9	8.4	7	110	240
1970-1974	87.7	0.24	6.7	8.4	21	590	740
1975-1979	276.6	0.24	2.0	8.4	66	550	2 330
1980-1984	513.7	0.24	0.9	1.9	120	460	990
1985-1989	936.0	0.24	0.4	0.2	220	390	150
1990-1994	1146.7	0.24	0.4	0.1	280	490	150
1995-1997	767.2	0.24	0.4	0.1	180	320	100
Total					900	2 900	4 700

Table 47
Estimated amount of ^{131}I used in medical radiation therapy

Health care level	*Fraction of world population*	*Treatments per 1,000 population*		*Total activity administered* [a] *(TBq)*
		Thyroid cancer	*Hyperthyroidism*	
I	0.26	0.038	0.15	410
II	0.53	0.01	0.02	190
III	0.11	0.0027	0.017	15
IV	0.10	0	0.0004	-
Total (rounded)				600

a Assumes total world population of 6 10^9 and average amounts administered per treatment of 5 GBq (thyroid cancer) and 0.5 GBq (hyperthyroidism).

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ANNEX D

Medical radiation exposures

CONTENTS

Page

INTRODUCTION

1. Over the last 100 years, ionizing radiation has been increasingly applied in medicine and is now firmly established as an essential tool for diagnosis and therapy. The overwhelming benefits accruing to patients from properly conducted procedures have fostered the widespread practice of medical radiology [A22], with the result that medical radiation exposures have become an important component of the total radiation exposure of populations.

2. Since beginning its work in 1955, the Committee has regularly monitored the medical uses of radiation as part of its continuing review of sources of exposure. The most recent analysis, included in the UNSCEAR 1993 Report [U3], covered the period 1985–1990, but information available since 1970 was cited in order to investigate trends in usage and doses. The Committee concluded that medical applications are the largest man-made source of radiation exposure for the world's population, although there was still a far from equitable distribution of medical radiation services in different countries with different levels of health care; whereas the 1993 worldwide estimate for the annual per caput dose from diagnostic examinations was 0.3 mSv, corresponding average values for countries of the upper and lower health-care levels were 1.1 mSv and 0.05 mSv, respectively. A century after Röntgen's seminal discovery of x rays, some two thirds of the world's population still lacks adequate diagnostic imaging and radiation therapy services [W12].

3. The Committee also concluded that population exposures from the diagnostic and therapeutic uses of ionizing radiation were likely to be increasing worldwide, particularly in countries where medical services are in the earlier stages of development [U3]. However, further and more comprehensive analyses would be required in order to refine global estimates and establish important trends.

4. The need for such analysis is heightened by a number of underlying factors that could affect the practice of radiology, in terms of both the type and frequency of procedures carried out and the associated levels of dose to individual patients [S60]. For example, population growth, urbanization, and longer lifespans can be expected to result in growing demands for medical radiology [U3]. Conversely, as a general trend some reductions in dose can be expected to arise from continuing advances in the technology for ionizing radiation and its substitution by non-ionizing radiations, more widespread and formalized implementation of quality assurance procedures in radiology departments, better training of staff involved in medical radiology [I2], and more rigorous standards for patient protection [I3, I5, I17].

5. Accordingly, this Annex presents the results of an updated, broad review of medical radiation exposures. Its purpose is to provide new qualitative and quantitative information on the frequencies and doses for diagnostic and therapeutic procedures, to assess medical radiation exposures worldwide, to make comparisons with data from previous reviews, and to explore temporal or regional trends in the practice of medical radiology. Although the review is not intended as a means to optimize procedures or as a guideline for radiation protection, it will nevertheless provide the background for such work.

I. SCOPE AND BASIS FOR THE ANALYSIS

A. MEDICAL RADIATION PROCEDURES

6. This Annex is principally concerned with exposures received by patients from the use of radiation generators or radionuclides as part of their diagnosis or treatment (Chapters II–V). Medical exposures are also conducted for medico-legal reasons and on volunteers (patients or healthy persons) for the purposes of research; this latter category of exposures is considered in Chapter VI. The information on patient exposures reported for different types of procedure in various countries is assumed to reflect routine practice, although a brief discussion of radiation incidents in medicine is included in Chapter VII for the purpose of illustration. Exposures received by medical staff from medical radiology are discussed elsewhere, in Annex E, "*Occupational radiation exposures*". Exposures of the general public arising from contact with patients undergoing therapy with sealed or unsealed radio-nuclides, the disposal of radioactive waste from hospitals, and the production of radionuclides for medicine are considered in Annex C, "*Exposures to the public from man-made sources of radiation*".

7. Diagnostic procedures, in particular the widespread use of x rays, are the most common application of radiation in medicine. The range of x-ray techniques used, such as radiography, fluoroscopy, computed tomography, interventional radiology, and bone densitometry, are discussed in Chapter II. There is also significant practice in imaging and other functional studies involving administrations to patients of unsealed radionuclides; these uses are described in Chapter III. Such nuclear medicine and x-ray procedures are intended to provide doctors with diagnostic information and in principle are conducted with the lowest practicable levels of patient dose to meet clinical objectives [M39, S54].

8. In contrast, therapeutic exposures are less frequent and the levels of dose are very much higher in view of the quite different purpose. Radiotherapy is used mainly for the treatment of cancer, where the intention is to deliver a lethal dose to malignant tissue within a well-defined target volume, while minimizing the irradiation of surrounding healthy tissue. Many patients receiving radiotherapy have a limited life expectancy owing to their age or disease. Treatments are most often carried out using radiation generators and sealed radionuclide sources. Teletherapy and brachytherapy techniques are considered in Chapter IV. A small amount of therapy practice involves the administration of unsealed radionuclides, and this technique is discussed in Chapter V.

9. In addition to diagnostic imaging or therapy, there are also some other applications of ionizing radiation for tissue analysis in the clinical assessment of health or disease, mostly in the course of research projects. For example, *in vivo* neutron activation analysis, based on the detection of characteristic gamma rays produced by the interaction of neutrons within the body, has been used to measure calcium, nitrogen, and cadmium, with whole-body doses up to 10 mSv [C12, S28]. Also, x-ray fluorescence techniques have been used for *in vivo* measurements of iodine, lead, and cadmium [C12]. However, such exposures are not a widespread practice and are not considered further in this review.

B. SOURCES OF DATA

10. The broad characterization of practice in medical radiology requires a knowledge of the frequency of each type of procedure and the associated levels of patient dose. To be able to provide as complete an assessment as possible of global practice in medical radiology, the Committee conducted a worldwide survey of medical radiation usage and exposures by means of a widely distributed questionnaire soliciting systematic information for the years 1991–1996. This Annex summarizes all data submitted to the Committee up to the end of 1999. The questionnaire was similar to that employed for the previous review [U3], although the format was revised to improve the quality and utility of the data collected. Information was sought on national facilities for radiological examinations and treatments, together with specific data for important types of procedure: annual numbers of procedures, age and sex distributions of patients, and representative doses. Respondents to the UNSCEAR Survey of Medical Radiation Usage and Exposures are listed in the References, Part A.

11. The availability of detailed national data on medical radiology practice varies considerably even in developed countries. For example, periodic surveys of national practice are conducted in some countries (see, *inter alia*, [O6, S61, S62, S63, T16, Z17]). The information on, say, frequency and dose provided to the Committee in the present survey was therefore often based on limited data from a particular region or even an individual hospital; these data were then assumed, with appropriate scaling, to be representative of the entire country. When known, such instances of extrapolation are generally identified in the footnotes to the tables. The interpretation of non-standard or incomplete dosimetric information provided in the questionnaires is discussed in detail in the appropriate Sections below.

12. The valuable information provided by responses to the UNSCEAR Survey of Medical Radiation Usage and Exposures has been supplemented by selected data from publications following an extensive review of the literature. These are used in particular when discussing specific practices and illustrating trends.

C. DOSIMETRIC ASPECTS

13. Medical exposures to individual patients are summarized most completely in terms of the absorbed dose to each organ or tissue of the body, although this approach is often difficult to realize in practice, particularly for any large-scale dose survey. Weighted-organ dose quantities, such as effective dose equivalent [I7] and effective dose [I3], represent convenient indicators of overall exposure in the assessment of diagnostic practice (see, for example, [M33, O6]). They broadly reflect in a qualitative manner the risks to health of the stochastic (though not deterministic) effects associated with exposure to ionizing radiation. The Committee has previously used such quantities to evaluate patient doses [U3, U4, U6], with the express purpose of allowing a robust comparison of practice between, *inter alia*, types of procedure, countries, health-care levels, time periods, and sources of radiation.

14. However, the Committee has always indicated most strongly that these effective doses should not be used directly for estimating detriment (to individuals or populations) from medical exposures by application, for example, of the nominal fatality probability coefficients given by ICRP [I3]. Such assessments would be inappropriate and serve no purpose in view of the uncertainties arising from potential demographic differences (in terms of health status, age, and sex) between particular populations of patients and those general populations for whom the ICRP derived the risk coefficients. It has been suggested, for example, that effective dose could broadly underestimate the detriment from diagnostic exposures of young patients by a factor of about 2 and, conversely, could overestimate the detriment from the exposure of old patients by a factor of at least 5 [N1]. The analysis of radiation risk from diagnostic medical exposures requires detailed knowledge of organ doses and the age and sex of patients. Such analyses have been carried out (see, for example, [H18 , K12, K13, M23]), although this important topic is beyond the scope of this review and is not considered further.

15. Notwithstanding the above caveat, practice in diagnostic radiology is summarized in this Annex, for comparative purposes, principally in terms of effective

doses to exposed individuals undergoing each type of procedure and, taking into account numbers of procedures, collective effective doses over exposed populations. Other more practical dose descriptors are also used, as appropriate, in analysing diagnostic exposures. These are discussed more fully below for examinations with x rays (Section II.B) and radiopharmaceuticals (Section III.B). The typical dose values quoted for specific examinations are generally arithmetic mean values, summarizing distributions of measurements over groups of patients or hospitals that are often wide and highly skewed.

16. Diagnostic practices may also be characterized in terms of per caput doses, by averaging collective effective doses over entire populations (including non-exposed individuals). Although such doses provide a broad indication of practice, they tend to conceal significant variations in the patterns of exposure received by individuals; some individuals might have a considerable number of x-ray examinations in their lifetime and others might have none at all. For example, it was estimated in 1992 that about 1% of the population of the United Kingdom received a lifetime dose of more than 100 mSv from medical x rays, yet the annual per caput effective dose was about 0.4 mSv [H9]. It has also been observed that radiological examinations are performed somewhat more frequently in terminally ill patients [M50], with about 5% of all the diagnostic x-ray and nuclear medicine procedures at one institution in the United States involving patients in their last six months of life, who collectively represented about 2% of the total number of patients examined [M19]. A study in Germany found that of the 60% of patients admitted into two large hospitals who underwent diagnostic x-ray procedures, about 6% received only 1 exposure, although the proportions receiving more than 12, 50 and 100 exposures were 24%, 6% and 1%, respectively [M73].

17. Although effective dose is used in this Annex, with some caution as discussed above, in the evaluation of patient doses from diagnostic exposures, this quantity is inappropriate for characterizing therapeutic exposures, in which levels of irradiation are by intent high enough to cause deterministic effects in the target volume. After due consideration of the complex issues involved, the Committee previously included broad estimates of collective effective dose for therapeutic exposures, computed on the basis of scattered radiation outside the target volumes. This was done to provide a robust assessment of practice for the purposes of comparison within a comprehensive review [U3]. The present analysis, by contrast, summarizes therapy largely in terms of frequency of practice, together with some information on prescribed doses. It is recognized, however, that assessing risk from the irradiation of non-target organs may be of particular importance for young patients who are successfully cured by radiotherapy for, say, Hodgkin's disease (see, for example [V27]), or for patients undergoing radiotherapy for inflammatory disease.

D. ASSESSMENT OF GLOBAL PRACTICE

18. The availability, complexity, and utilization of radiological equipment for imaging and therapy varies widely from country to country. In the inevitable absence of comprehensive information on national practice from all countries, particularly those in the least developed regions of the world, the assessment of global activities in medical radiology requires extrapolation from the limited data available from the questionnaires or the published literature. Models for doing this were developed in the UNSCEAR 1988 and 1993 Reports [U3, U4] on the basis of observed broad correlations between the number of x-ray examinations per unit of population and the number of physicians per unit of population. Accordingly, information on the number of physicians per million popula-tion, which is in general a more widely available statistic, can be used to scale diagnostic x-ray frequencies from a few countries to all regions of the world. As part of this global model, countries are categorized into four levels of health care according to broad ranges for the number of physicians per unit of population: health-care level I (at least 1 physician per 1,000 population), health-care level II (1 physician for 1,000–3,000 population), health-care level III (1 physician for 3,000–10,000 population), and health-care level IV (1 physician for more than 10,000 population). It should be emphasized that this classification of countries is used solely for the purposes of modeling and does not imply any judgements on the quality of health care.

19. Since diagnostic x-ray examinations represent the main source of exposure for populations, stratifying countries according to health-care level provides a robust model for assessing general worldwide frequencies and collective doses from practice in medical radiology. For the present analysis, information on the number of physicians per unit of population has been taken principally from data provided to the Committee in the questionnaires or from survey data published by WHO on human resources for health in the years 1988–1991 [W20]. The annual numbers of diagnostic medical x-ray examinations reported by different countries span several orders of magnitude. Figure I illustrates correlations between these annual totals in countries of different health-care levels and either the population or the total number of physicians in those countries. In general, annual numbers of examinations appear broadly to correlate better with national totals of physicians (Figure Ib) than with populations (Figure Ia), this being in general agreement with the model. For completeness, Figure II presents the relationship between dental x-ray examinations and either the population (Figure IIa) or the number of dentists (Figure IIb). However, there could be confusion as to whether the reported national totals for dental x rays refer to numbers of examinations or numbers of films. Also, it is likely in developing countries that significant numbers of dental x-ray examinations are conducted in hospitals rather than in dental practices.

20. There are clearly limitations to this broad classification system. For example, there will be differences in how different countries define a "physician", and these

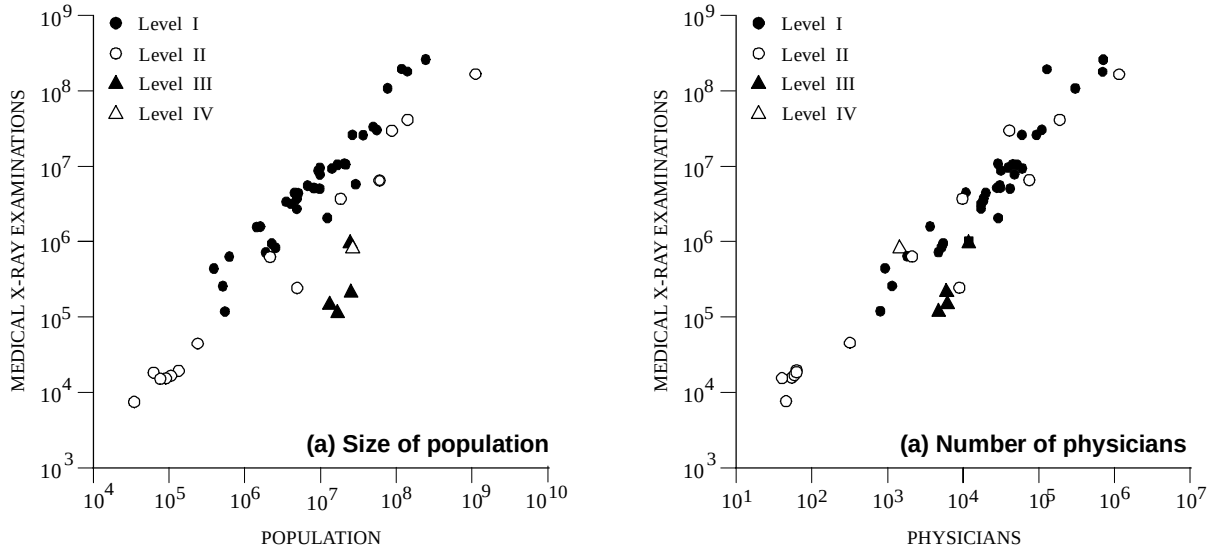

Figure I. Annual number of diagnostic medical x-ray examinations in relation to (a) size of population and (b) number of physicians.

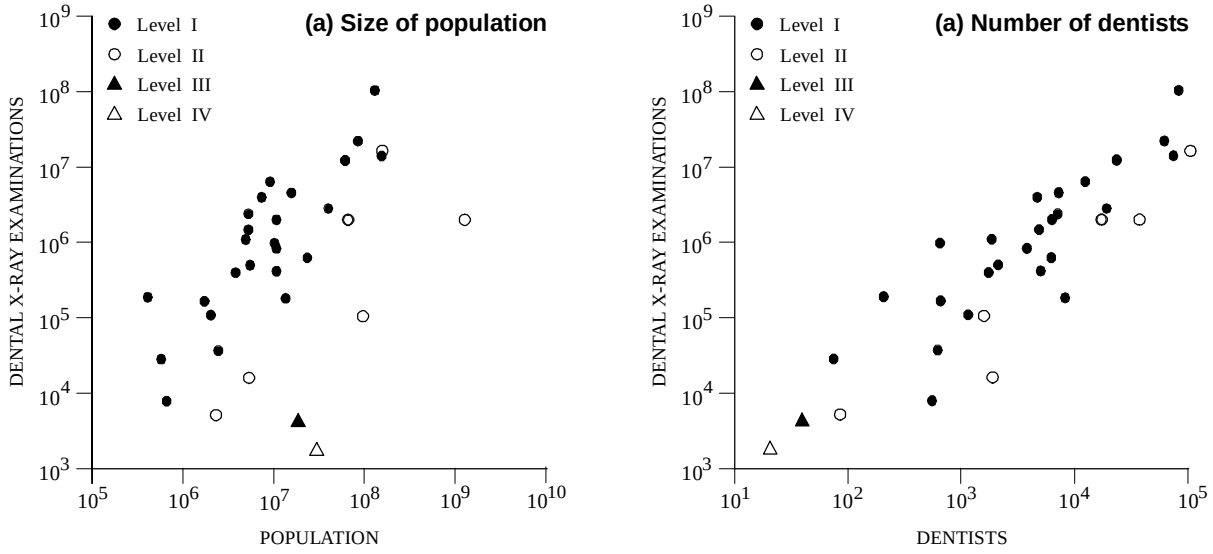

Figure II. Annual number of diagnostic dental x-ray examinations in relation to (a) size of population and (b) number of dentists.

lead to uncertainties in the data on numbers of physicians. Also, assigning countries to health-care levels on the basis of average national data will hide possibly significant regional variations within countries, particularly for large ones [U3]. Some examples can be given below in relation to Latin America [B33]. In Argentina, Brazil, Colombia, Costa Rica, Mexico, and Venezuela, the numbers and variety of radiological studies performed in university and regional hospitals are comparable to those performed in similar centres in more developed countries. In those large countries with high levels of urbanization, the main hospitals often tend to be private, and these establishments have relatively modern and sophisticated imaging services. In those countries with intermediate-sized populations, the range of diagnostic equipment and services available is usually not as great, with resources concentrated in capital cities and regional centres.

21. The global model can be expected to provide only a very broad characterization of overall national practice in medical radiology. For example, South Africa is assumed in the present analysis to fall in health-care level I, although significant variations are reported in the frequency of x-ray examinations between race groups, ranging from 67 per 1,000 blacks to 460 per 1,000 whites [H29, M22]. Ecuador is classified in health-care level I, although the indicators of national radiology practice are rather less than the average levels for this category. Some countries have been classified in levels different from those to which they would have been assigned based strictly on the number of physicians. Examples are Jordan, Libyan Arab Jamahiriya, Mexico and Turkey (level II rather than level I) and Sudan (level III rather than level II). The provision of health-care is broadly influenced by national economic status, and WHO has, for analytical purposes, also classified countries according to the following

scheme [W21]: least developed countries (LDCs); developing countries (excluding LDCs); economies in transition; and developed market economies. The Committee might wish to explore this approach for potential application in future assessments of global medical exposures.

22. Continued use of the same global model in this Annex as that adopted by the Committee for its previous analyses [U3, U4] ensures consistency of approach and allows the comparing of practice between different levels of health care and periods of time. The total population of the world in 1996 was estimated to be 5,800 million [W21]. Table 1 presents a breakdown of this present total by health-care level according to the global model, together with similar data reported for analyses in previous years. Ideally, this model should have access to additional national data on medical radiation usage. For example, information on the frequency of medical x-ray examinations is presently available from 36 countries in health-care level I, which collectively represent 67% of the total population of that health-care level; for other health-care levels, data are available from 14 countries in level II (representing 50% of the total population in the level), 4 countries in level III (representing 13% of the total population in the level), and only 1 country in level IV (representing 5% of total population in the level). Overall, information on x-ray usage is available for 46% of the world population. Such relatively small sample sizes necessarily demand that some caution is exercised when interpreting the results of the present analyses.

23. Medical radiology is practiced under widely differing circumstances, even in well-developed countries in the upper levels of health care, in terms of the size and nature of the facilities where the procedures are conducted, whether they are in the public or private domain, and the specialist training of the medical doctors and support staff. Basic data on medical radiation resources for 1991–1996, acquired from responses to the questionnaire and other sources, are tabulated in Tables 2–8: numbers of physicians and dentists (Table 2), diagnostic imaging equipment (Table 3), diagnostic imaging equipment per million population (Table 4), radiotherapy equipment (Table 5), radiotherapy equipment per million population (Table 6), temporal trends in average provision for medical radiology per million population by health-care level (Table 7), and annual numbers of medical radiation examinations and treatments (Table 8). The global use of medical radiology is summarized in Table 9. The symbol «-» is used in these and subsequent tables to indicate where data were not available, whereas zeros indicate the complete absence of a practice or type of equipment.

24. In general, there are broad trends for lower mean levels of resources and practice when comparing values derived for health-care level I with those derived for the lower levels (II to IV). However, significant differences are often apparent between individual countries within the same health-care level. Also, the amounts of data available in particular for the lower health-care levels (III and IV) are limited. The results of such reviews should always be used with some caution and interpreted only in the full knowledge of uncertainties in the reliability and representativeness of the national data presented [R21]. These data will have been derived using a variety of different methods and designs of survey and there may, for example, be significant bias in national estimates extrapolated from data for a single region or institution because of the wide variations in practice that inevitably exist within countries [A15, A21, K18, P16, S38, W33]. There will also be differences in interpretation between countries in relation to categories of staff (for example physician), equipment (for example brachytherapy units) and procedure (for example, the potential confusion between x-ray film or examination). In addition, the detailed data on frequency and dose subsequently reported in this review are subject to uncertainties arising from the exact scope of the examination groupings used (in relation, for example, to the broad x-ray categories of "Abdomen" or "Head") and the methods (including calibration) employed for dose assessments. Furthermore, it should be noted that the averaging of data within health-care levels has often been carried out over different populations and this could be important when comparisons of mean values are being made, particularly in relation to temporal trends utilizing data for the different periods of time from previous reviews.

E. SUMMARY

25. The exposure of patients to ionizing radiations for medical diagnosis and therapy has been assessed on a global scale utilizing survey data on national practice provided by a questionnaire on the resources for medical radiology and the frequencies and doses for different types of procedure, supplemented by a review of the published literature. Available data have been scaled up to provide estimates for the world population on the basis of a global model in which countries are categorized into four health-care levels according to the commonly-available metric of number of physicians per unit of population. Notwithstanding some differences in the quality and reliability of the national data and the broad method of extrapolation, the model provides a robust assessment of global practice in medical radiology for the purposes of comparison with previous data and the assessment of trends.

II. DIAGNOSTIC RADIOLOGY

26. Diagnostic examinations with x rays have been used in medicine for over a century, although with increasing sophistication; key technical advances are summarized in Table 10. During the last 20 years in particular, medical imaging has experienced a technological revolution, and it now allows the improved imaging of anatomy, physiology, and metabolism [H1]. Steady advances in the quality of x-ray images and in patient protection have ensured a continuing role for diagnostic x rays in health care, although alternative modalities for diagnosis are becoming increasingly available, such as ultrasound, endoscopy, and, particularly in developed countries, MRI. Nevertheless, because x-ray examinations remain the most frequent use of ionizing radiation in medicine, they are the most significant source of medical exposure for the world population. An increasingly wide range of equipment and techniques is employed to meet a diversity of diagnostic clinical purposes.

A. TECHNIQUES OF EXAMINATION

27. Traditional x-ray examinations involve static imaging, which uses film in cassettes with intensifying screens (radiography), and dynamic imaging, which uses (electronic) image intensifiers (fluoroscopy). Cine film (35 mm) is also used in radiological studies of the heart. Radiographic exposures are commonly performed during fluoroscopy, often using a 100 mm film camera linked to the intensifier (photofluorography), although digital radiographic techniques are increasingly being introduced. The visibility of particular tissues can be enhanced by the introduction of contrast media into the patient, such as barium for the gastrointestinal (GI) tract and iodine for the blood vessels (angiography), the urinary system (urography) or the biliary system (cholecystography). In addition to fixed installations in hospital departments and practices, mobile equipment for radiography or fluoroscopy allows imaging in the wards or operating theatres. Radiography is occasionally conducted in the homes of patients by visiting radiographers using portable x-ray units.

28. Digital methods for the processing and display of x-ray images were first introduced into clinical practice with the advent of CT in 1972. This revolutionary technology was able to provide high-quality images of isolated slices of the patient using a thin rotating beam of x rays, albeit with relatively high patient doses. The subsequent development of helical CT has lead to further scanning techniques such as CT endoscopy and CT fluoroscopy. Continuing advances in computer technology have also promoted the general development of digital radiography, where images are acquired in digital form, most commonly from an image intensifier (digital fluorography) or from a storage phosphor plate (computed radiography) [H1]. Other detector systems for indirect (with an intermediate phosphor) or direct digital radiography, utilizing for example amorphous selenium and amorphous silicon, are under development [R22, Y4]. The technique of digital subtraction angiography (DSA) is based on digital image processing with logarithmic subtraction and edge enhancement; it is used increasingly for the visualization of blood vessels throughout the body. Such improvements in imaging and innovations in other equipment, such as needles, guidewires, catheters, stents, and contrast media, have facilitated the development of interventional radiological techniques, in which imaging helps to guide therapeutic procedures and to deliver therapeutic agents [A19]. Digital technology also provides for the storage and transfer of images within and between hospitals and their transmission for remote consultation (teleradiology) using digital networks known as picture archive and communications systems (PACS).

29. In addition to examinations on symptomatic patients with specific clinical indications, diagnostic x-ray examinations are also undertaken in connection with mass screening programmes of sections of the population. These may be for the purposes of, for example, diagnosing tuberculosis, breast cancer or, particularly in Japan, stomach cancer, and managing occupational health [N1]. Furthermore, some examinations are conducted for medico-legal reasons and others on volunteers participating in medical research.

B. DOSIMETRY

30. The levels of dose to patients undergoing diagnostic examinations with x rays are in principle determined by the quality of images required and the extent of investigation necessary to meet specific clinical objectives. In practice, numerous factors relating to both the radiological equipment and the procedures in use have an influence on the imaging process. Some of the more important aspects of practice that have a broad impact on patient dose are summarized in Table 11; this information represents an updated version of a similar list given in the UNSCEAR 1993 Report [U3]. Patient size is, of course, an additional determinant of dose for individual examinations [S58], although this factor cannot be used generally to improve practice. Accordingly, comparisons of dose to assess relative performance are made in terms of mean values observed over groups of patients or in relation to standard-sized patients.

31. Because x-ray procedures characteristically involve a series of partial-body exposures, they produce complex patterns of energy deposition within the patient and various dose measurement strategies are necessarily employed [F17, N27]. Organ doses are in general difficult to assess, and in practice routine patient monitoring is usually based on directly measurable dose quantities, such as entrance surface dose (with backscatter [P17]) per radiograph and, particularly for complex procedures involving fluoroscopy, dose-area product per examination [B46, K25, L14, L27,

N9]. Dose-area product meters are increasingly being fitted to x-ray equipment and their development has continued so as to allow also the display in real-time of dose rate and cumulative dose [G14, R23]. The quantities entrance surface dose and dose-area product are often measured as part of quality assurance programmes or in other surveys of practice [B55, M41, P27]. Dose assessments reported in this manner are widely used in this Annex and assumed to be reliable, although essential details of dosemeter calibration [D30, G27, G52, N9] are often unknown. From a radiation protection point of view, the types of dose measurement discussed above have also formed the practical basis, both nationally [L16, N1, Z17] and internationally [C6, I5, N24, S57], for specifying reference values (diagnostic reference levels) for common diagnostic x-ray examinations, as a way of promoting improvements in practice [I17, O11, W38]. In addition to measurements on patients, assessments of dose performance at x-ray facilities are also conducted by calculation [B50] and by using patient-equivalent phantoms to provide indications of dose and dose rates under standard conditions of exposure [M28, M40, R15, S44, W39].

32. Organ dose and effective dose [B45] are generally estimated from routine dose measurements using conversion factors appropriate to the conditions of exposure; coefficients that have been used in various dose studies are reviewed elsewhere [R11]. These coefficients may be derived experimentally on the basis of physical anthropomorphic phantoms (see, for example, [M21, M44, R11]) or calculated using Monte Carlo simulation techniques with mathematical phantoms (see, for example, [S56, T9, Z15, Z16]). Theoretical normalized organ dose data are available *inter alia* in relation to routine examinations of adults (see, for example, [D7, H15, R9, S11]), paediatric patients (see, for example, [H16, R10]), and cardiac [S9] and angiographic [K27] examinations, although care is needed when applying such coefficients to clinical practice [P19, W35]. The comparison of organ and effective doses derived from measurements and calculations under similar conditions of exposure indicates reasonable agreement between the methods and highlights the limitations and uncertainties in both approaches [M48]. Computational methods of dosimetry in particular are advancing steadily, with the development of more realistic (voxel) phantoms based on digital images of humans [D5, J6, V24, X1, Z24]. Differences in the results from calculations for different anthropomorphic phantoms under similar conditions of exposure underline the uncertainties in such computed dose coefficients, which should not be applied to examinations of individual patients [Z25].

33. Assessment of the weighted dose quantity of effective dose is particularly problematic for the very localized and low levels of exposure involved in dental radiology, in which doses to the so-called "remainder organs" are dominant [L37]. For example, for given sets of organ dose data from dental exposures, the values of effective dose [I3] have been reported to be less than the corresponding values of effective dose equivalent [I7] by factors of 2–10 [K42, U3]. Such differences in interpretation represent an additional source of uncertainty that should be borne in mind when comparing reported effective dose data.

34. For the intensive imaging procedures used in interventional radiology, a knowledge of the localized dose to skin is also important with respect to the potential for deterministic effects of irradiation [C2, G34]. Such cumulative skin doses can be assessed by calculation (see, for example, [G17]) or measured directly on the patient using film (see, for example, [F14, K21, L25, V10]) or thermoluminescent dosemeters (TLDs) (see, for example, [G18]) or solid-state detectors (see, for example, [P18]), or by portal monitoring [W43]. It is also possible to make simultaneous measurements of cumulative dose and dose-area product during fluoroscopic examinations using a single transmission ionization chamber [G14].

35. Special dosimetric techniques are often employed in the case of mammography and CT in view of the peculiar conditions of irradiation for these examinations [D40, J13, Y13, Z19]. Practice in mammography is generally assessed in terms of the mean dose to glandular tissue, derived in relation to a standard breast thickness using coefficients normalized to measurements of air kerma made free-in-air (see, for example, [B67, F20, H17, H49, K44, L15, N37, S83, Y2, Z2, Z20]), although direct measurements of entrance surface dose on patients have also been employed [G11, Z2]. Effective doses from mammography are included in the present analysis for completeness, although this quantity is not an appropriate indicator of risk for such exposures of female patients. Estimates of risk should be based on the mean dose to glandular tissue and age-specific risk factors.

36. CT generally involves the irradiation of thin slices of the patient in rotational geometry by a fan beam of x rays. The principal dosimetric quantity in CT is the computed tomography dose index (CTDI), in which the dose profile along the axis of rotation for a single slice is averaged over the nominal slice thickness [S7]. The CTDI can be measured free-in-air [S8] or in homogeneous CT dosimetry phantoms for the head and body [C36, K11, L20], although such reported values can reflect subtle differences in the definition of CTDI [E3]. A related quantity, the multiple scan average dose (MSAD), provides an indication of the dose in a phantom for a series of multiple scans with a constant separation [S7]. Organ doses and effective doses to patients for particular scanning protocols can be estimated [K41, S30] using dose coefficients provided by mathematical modeling, which are normalized to a free-in-air axial dose [B64, C37, H43, J3, J12, W49, Z5, Z6], or by dose measurements with TLDs in phantoms [N16]. Other dosimetric quantities of interest that are under development for characterizing practice in CT include dose-area product [P5] and dose-length product [E4, S40] in relation to CTDI measurements in standard phantoms; these quantities in turn allow the broad estimation of effective dose to patients [H42, J13].

37. Whereas organ doses and effective doses generally provide the most complete assessment of x-ray exposures, an alternative dosimetric method focuses on the energy imparted as a practical measure of patient dose [A7, A24, G13, P6]. Such values of energy imparted allow estimates of effective dose to be derived for the exposure of both adult and paediatric patients [A1, A3, H5, H38]. Biological dosimetry, based on an analysis of chromosome aberrations in human lymphocytes, has also been reported for patients who received extensive exposure to diagnostic x rays [W17]. However, this technique is of limited importance in routine practice.

C. ANALYSIS OF EXPOSURES

1. Frequency of examinations

38. The annual numbers of diagnostic medical x-ray examinations reported by different countries for 1991–1996 span several orders of magnitude. The annual frequencies (numbers of examinations per 1,000 population) are summarized by type of procedure in Table 12, with countries grouped according to health-care level. Part A includes information for some common types of examination and Part B for some special procedures and also the total of all medical x-ray examinations. The percentage contributions of each type of examination to total frequency are given in Table 13. Mean values of frequencies have been derived for each health-care level by dividing the total numbers of procedures by the total population.

39. There are significant differences in the patterns of practice from one country to another, even within the same health-care level. Many of the reported data were obtained from surveys or registrations that were complete enough to give representative results. In other cases, however, figures have been estimated from smaller or more localized samples that might not adequately reflect national practice. There may also be some differences in the examination categories used in national surveys. Some particular qualifications noted for the present data are given in footnotes to Tables 12 and 13. National annual frequencies for the total of all medical x-ray examinations vary by a factor of nearly 10 within the sample of 36 countries listed in health-care level I (151–1,477 examinations per 1,000 population); smaller variations exist in the samples of 14 countries in level II (98–306 examinations per 1,000 population), and 4 countries in level III (7–37 examinations per 1,000 population). Information was available from only one country in health-care level IV (the United Republic of Tanzania: 29 examinations per 1,000 population). The average total frequencies for levels II and III are factors of 6 and 50, respectively, smaller than the average for level I, 920 examinations per 1,000 population.

40. The relative use of fluoroscopy and photofluorography also varies between countries. For example, the percentage contribution from fluoroscopic procedures to the annual total of all medical x-ray examinations is about 4% in Russia, 9% in Ukraine [K18], 10% in Germany (with many of these examinations involving long exposure times) and 28% in Romania [D28]. In China [Z13], chest fluoroscopy accounts for 62% of all x-ray examinations. Photofluorography accounts for about 16% and 32% of all x-ray examinations in Romania [D28] and Russia, respectively, and for 55% of all chest radiography in Poland [S49].

41. In general, examinations of the chest are the single most important type of procedure; the relatively low frequencies reported for Sudan and the United Republic of Tanzania, for example, are apparently due to incomplete survey data. Significant contributions to practice in all health-care levels are made by examinations of the limbs and joints and the spine. The more complex procedures summarized in Part B of Tables 12 and 13 are in general performed less frequently in the countries of lower health-care levels. The decreased use of CT in levels II–IV relative to level I can, however, be viewed against a relative increase in conventional examinations of the head. Temporal trends in the frequency of examinations are discussed Section II.E.

2. Exposed populations

42. The distributions by age and sex of patients undergoing various diagnostic x-ray examinations in 1991–1996 are presented in Table 14 for selected countries of the four health-care levels; some known limitations in the reported data are given in the footnotes. The analysis uses the same three broad ranges of patient age as the UNSCEAR 1993 Report [U3]. It has already been noted that the populations of patients undergoing diagnostic examinations with x rays are in general older than the corresponding whole populations, although significant numbers of procedures are conducted on children [U3]. Some differences in patient age distribution are apparent from country to country for a particular type of examination, even when considering a single health-care level. However, the population-weighted mean values for each level suggest some general trends in the age/type of examination and age/health-care level relationships. For example, older patients predominate for examinations of the gastrointestinal tract, urography, and cholecystography, whereas children form a substantial fraction of the patients undergoing examinations of the limbs and joints, head, and pelvis and hip. In general, greater proportions of examinations are conducted on patients in the two younger age groups for countries in levels II–IV than for level I countries. This finding is broadly consistent with the observation that there is a bias towards younger ages in the general population for many developing countries [U3].

43. Notwithstanding specific examinations such as mammography and pelvimetry, the male vs. female distributions of diagnostic x-ray examinations do not deviate greatly from the underlying patterns for whole populations. There are, however, some variations between countries in the data reported for each particular type of procedure.

3. Doses from specific types of examination

44. The typical effective doses to patients from medical x rays reported by different countries for 1991–1996 are presented in Table 15. Part A includes mean values of effective dose for some common types of examination and Part B for some special procedures and also the annual total of all medical x-ray examinations. Representative values of other dosimetric quantities used to characterize patient doses from x-ray examinations are summarized for different countries in Table 16. Part A includes mean values of entrance surface dose for some common types of radiograph and Part B mean values of dose-area product for some specific, more complex diagnostic x-ray examinations involving fluoroscopy. Further patient dose data have been published in connection, for example, with examinations of the cervical spine [M22, N15, O3, R11], extremities [H21, M22, O3], hysterosalpingography [C29, F16, G28, S51], barium studies of the gastrointestinal tract [C30, D29, G29, G30, L29, L49, M38, S52, W37, Y10, Z14] and extracorporeal shock wave lithotripsy (ESWL) [M47]. Studies have also been conducted of the dose rates during fluoroscopy (see, for example [B51, B52, S53]). Dose rates have been reported in relation to some different organs of patients undergoing x-ray examinations in Bangladesh [B44]. X rays are also used in chiropractic [B29, E12] and podiatry [A23]. The dosimetric aspects of some specific procedures are discussed further below.

(a) Angiographic and interventional procedures

45. Advances in technology for imaging and ancillary equipment have facilitated the development of increasingly complex radiological procedures for angiography and interventional radiology [B49, C25] and specific methods are required for assessing and monitoring the resultant patient doses [B57, F18, G34, G35, G36]. Angiographic examinations involve complex patterns of imaging [K28] and are often complementary to interventional procedures, providing evaluations before and after treatment. Some reported dose data for different types of angiographic procedure are given in Table 17. Doses to patients from interventional radiology procedures are summarized in Table 18.

46. A survey of practice in five European countries identified over 400 different types of interventional procedures involving a range of medical imaging specialities, such as neuroradiology, vascular radiology, and cardioangiography [M8]; typical data from Germany for 1990 indicated that nearly 60% of such procedures fall within the broad category of angioplasty (dilatation), with significant applications also in biopsy/drainage (11%), pain therapy (11%), embolization (7%), and genitourinary (7%) and biliary (5%) interventions. Such interventional procedures are generally complex and can involve significant periods of patient exposure, although these types of therapy often represent alternatives to more hazardous surgery or are the sole method of treatment. Interventional radiology is already an established part of mainstream medicine and is likely to expand further with the continuing development and adoption of new procedures [B1], particularly in countries with well-developed health-care systems [J9, L11]. In Europe, the average rate of percutaneous transluminal coronary angioplasty (PTCA) procedures in 1993 was 343 per million population, an annual increase of 12% over previous data for 1992, but with considerable variation among national practices, from Romania (1 per million) to Iceland (876 per million) [U15]. Information on interventional cardiology in Spain (practiced at 81 hospitals) indicated a total of 90,915 procedures in 1997 (a rate of 2,270 per million population), with 72,370 (80%) being diagnostic (increase of 13% relative to 1996) and 18,545 (20%) being therapeutic (increase of 24% relative to 1996).

47. Dose rates during such sophisticated procedures can be relatively high, for example up to a regulatory maximum of 180 mGy min^{-1} at the patient surface during high-level-mode fluoroscopy in the United States [C4]. Lower dose rates are technically possible, however, when using new techniques such as pulsed progressive fluoroscopy [H26]. The combination in interventional radiology of prolonged localized fluoroscopy, multiple radiographic exposures, and repeated procedures on particular patients can cause patient doses to reach levels associated with acute radiation injury of skin [C2, C14, W31]. Procedures of particular concern in this respect include radiofrequency cardiac catheter ablation, percutaneous transluminal angioplasty, vascular embolization, stent and filter replacement, thrombolytic and fibrinolytic procedures, percutaneous transhepatic cholangiography, endoscopic retrograde cholangiopancreatography, transjugular intrahepatic portosystemic shunt, percutaneous nephrostomy, and biliary drainage or urinary/biliary stone removal [F9]. However, there may in general be some under-reporting of skin injuries in view of the time delay between exposure and manifestation of damage. In the United States from 1992 to 1995, there were 26 reports to the Food and Drug Administration (FDA) of radiation-induced skin injuries from fluoroscopy [S46]. By 1999, the FDA had documented some 50 cases of radiation-induced burns, many involving cardiological procedures [A25]. Details have been published, for example, of occurrences of epilation [H23, K29], dermatitis [C21, D31, K22, P13, R24, S65, S66, V11], and erythematous lesions [S46, V11]. In one study of arrhythmia ablation procedures, about 6% of 500 patients were found to have received enough radiation exposure to reach the threshold dose (2 Gy) for early transient erythema, although no clinical manifestations of acute radiation-induced skin injury were observed [P14]. Another analysis of neurological procedures on 426 patients has suggested that long-term erythema may be encountered in 1%–2% of embolizations, with there being a potential for temporary erythema in 11% of both carotid procedures and cerebral angiograms, 3% of nerve block procedures, 7% of lumbar procedures, and 23% of embolization procedures [O7].

48. Dose data for different types of interventional procedure are summarized in Table 18: fluoroscopy time and, with due account of exposures from radiography, localized surface dose (measured or estimated assuming static beam), dose-area product, and effective dose. In general, fluoroscopy times are appreciable, and skin doses may approach or exceed the thresholds for deterministic effects [U3]. Some examples reported for particular patients can be given: a fluoroscopic exposure of 190 minutes and a localized dose of 8.4 Gy during radiofrequency ablation [C3]; an estimated maximum skin dose of 6.6 Gy from 110 minutes of fluoroscopy and 46 DSA acquisitions in the course of neurological embolization [H23]; an accumulated skin dose of 11–16 Gy from an estimated 90–120 minutes of fluoroscopy during cardiac radiofrequency ablation [V11]; and estimated maxima of 20 Gy and 3.5 Gy for skin exposure from fluoroscopy and DSA acquisitions, respectively, for a patient undergoing a series of biliary procedures over a four-week period [S46]. Doses may be significantly underestimated if contributions from cine exposures are not fully taken into account; the potential for skin injury will be underestimated if only fluoroscopy time is monitored, but overestimated when doses from different beam projections are combined [O14]. Notwithstanding significant variations between individual patients, values of dose-area product and effective dose for interventional procedures are typically larger than those for common diagnostic x-ray examinations; for example, dose-area product values of up to 918 Gy cm^2 have been reported during embolization procedures [B9]. One study comparing the use of conventional and digital systems for a range of interventional vascular procedures found mean values of dose-area product to be higher for the digital equipment in 13 out of 15 patient groups [R12]. Guidance concerning efficacy and radiation safety in interventional radiology is being prepared by WHO [B30, W9].

(b) Computed tomography

49. Technological developments to improve the quality and speed with which images are obtained have fostered the growth of CT practice throughout the world over the last two decades, allowing the routine performance of more and more extensive and elaborate examinations with relatively high levels of patient dose. The expanding use of CT in the diagnosis and assessment of cancer and other pathological conditions [D37, N35, R31] has made a substantial impact on both patient care and population exposure from medical x rays. In the United Kingdom, for example, the number of CT scanners in clinical use increased steadily following introduction of the technique in 1972 before finally reaching a plateau in 1995, as illustrated in Figure III. Whereas CT was estimated in 1989 to account for about 2% of the national total of all x-ray examinations and about 20% of the resultant collective dose, a further analysis for 1997 suggests that the latter figure may have risen to about 40% [S30]. Data from national surveys in eight other countries have confirmed as a general pattern the increasing importance of CT as a source of exposure for populations [S5]. In Germany during the years 1990–1992, CT accounted for, on average, about 3.5% of all x-ray examinations and about 35% of the associated collective effective dose, and further increases are foreseen [B31]. A similar analysis for Norway in 1993 indicated contributions from CT to x-ray frequency and collective dose of 7% and 30%, respectively [O12].

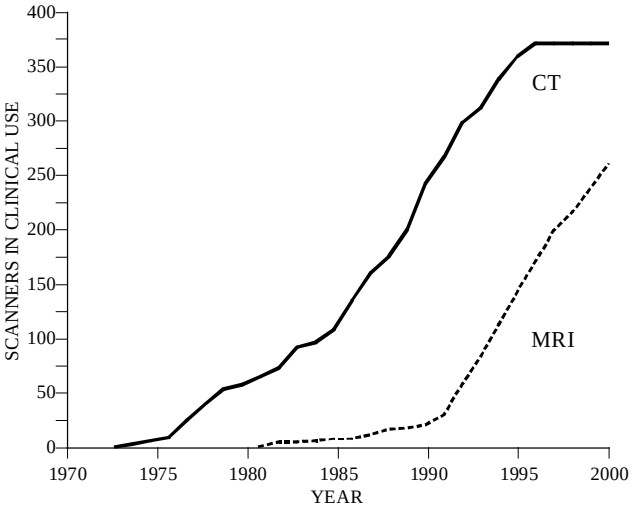

Figure III. CT and MRI equipment in the United Kingdom.

50. Mean values of effective dose reported by some surveys of CT practice are summarized in Table 19 for common types of procedure. In addition to apparent differences between such mean national data, there are also significant variations, for a given general type of procedure, in the typical doses at individual CT centres [O12, S40, S69, V15] and in the particular doses for individual patients [S70, W44]. Organ doses for CT procedures have been estimated in various studies on the basis of measurements [D32, E9, L31, M50, M51, N16, N30, N31, N32, P21] or calculations [H33, H34, O12, P22, T17]. In general, comparisons between sets of organ doses derived from measurements and calculations for a given examination technique demonstrate reasonable agreement when due account is taken of any differences in the exposure conditions being modeled [C31, G38, S71]. Absorbed dose to the lens of the eye may be above 50 mGy for certain CT procedures on the head [M52, M53, M54, M55, W45]. Doses to the thyroid, breast and testes from scattered radiation are significantly reduced when lead shielding is used [B59, H35, P23]. Reductions in breast dose during direct scanning have also been reported using an overlying bismuth filter [H36]. Lower levels of patient dose are often possible in CT with attention to choice of scanning technique [G39, K30], particularly with regard to lower settings [K32, M56, P24, R26, S72] or dynamic modulation [G40, H37, K31] of tube current. With the use of standard techniques, the energy imparted to the patient has been shown to increase with patient size, although the calculated effective dose is higher in children than adults [W46]: 6.0 mSv (newborn) and 1.5 mSv (adult) during head examinations, and 5.3 mSv (newborn) and 3.1 mSv (adult) during abdomen examinations [H38]. Significant

dose reductions have been reported in paediatric CT by the appropriate lowering of exposure settings [C32, S73, W47].

51. Clinical practice in CT has been stimulated in particular by the notable technical development in 1989 of helical (spiral) scanning [K33, K34]. This technique provides significant clinical advantages by allowing the rapid acquisition of image data over large volumes of the patient during a single breath hold [D33, H39]. Although image quality and patient dose in helical CT are broadly similar to those for conventional slice-by-slice imaging when equal or equivalent scan parameters are chosen, the speed and convenience of helical scanning is likely to promote increases in both the frequency of CT procedures and the levels of patient effective dose from procedures of increasing complexity [D34, M57, S10, T18, Z18]. However, the use of an increased pitch (>1) in helical scanning leads to a reduction in patient dose [M58] and such techniques have been successfully applied to clinical examinations to achieve lower doses for adults [C33, D35, H40, K35, P21, S74, S75, V16, W48] and children [R27]. The advent of the technology for helical CT has also facilitated the development of new techniques such as CT angiography [K36, K37, R28, R29], virtual CT endoscopy [P25], lung cancer screening CT [I26, N30, N33], and CT fluoroscopy [D36, K38, K39, S75]. This latter technique provides real-time reconstruction and display of CT images, with the potential for significantly high patient (and staff) exposure; preliminary studies have indicated, for example, patient skin dose rates of 190–830 mGy per minute during interventional CT fluoroscopy [N34] and an effective dose rate of 3.6 mSv per minute for abdominal scanning [A26]. The most recent innovation in CT has been the development of multidetector-array scanners that allow, for example, two [S93] or four [B60, H41, K40, O13] slices to be acquired in a single rotation in order to reduce scanning times for volume acquisition of data and improve longitudinal resolution. However, the radiation slice profiles and doses may be larger at all scan width settings for multi-slice scanners in comparison with single-slice systems under similar conditions of exposure [M59]. Such multislice scanning may also facilitate the further development of complex examinations with increased imaging of the patient and so potentially lead to increases in patient dose from CT.

52. Ultra-fast (sub-100ms) CT was proposed in the 1970's [I27] and developed in the 1980s using electron beam (EB) technology [B61, M60]. Such EBCT scanners have found particular application in the investigation of coronary artery disease [B62, L32, R30, T19], although their total number has remained relatively small: about 73 worldwide in 1997, with installations in the United States and Japan accounting for 47% and 26%, respectively [M61]. Doses from EBCT have been shown to be comparable to those from conventional CT scanning [M62, M63, S76], but higher than those from helical scanning [B63]. Analysis of EBCT practice at one institution indicates the following typical effective doses by type of procedure: 6.0 mSv for chest (25% of all EBCT), 7.2 mSv for abdomen (20%), 6.8 mSv for pelvis (10%), 2.4 mSv for head (3%), 2.0 mSv for cardiac function (multi-slice mode) (7%), 0.5 mSv for coronary artery calcification (single-slice mode) (30%), and 2.0 mSv for pulmonary emboli (5%) [M61].

53. In the longer term, CT may be partially replaced by MRI. This is already the imaging modality of choice for the central nervous and musculoskeletal systems, and applications are being refined for the chest and abdomen and in angiography [Z1]. The pace of change will be governed by the high cost and availability of MRI equipment [C34]. The provision for CT and MRI varies widely from country to country, even within the same health-care level; numbers of scanners per million population are summarized in Table 4. Whereas the number of CT scanners has probably reached a plateau in the United States, for example, increases can be expected elsewhere for some time. Further refinements in CT technology are likely [C35, D38, M64].

(c) Chest examinations

54. X-ray examinations of the chest are worthy of special mention in view of their high frequency. The thorax is one of the most technically challenging anatomic regions to image radiographically due to the large differences in tissue density and thickness present in the chest [R32]. The conventional chest radiograph, utilizing a film-screen detector, has proved a robust diagnostic aid over the last century [H44]. However, technological innovations have continued over the last decade in the quest for optimal imaging [L35, W50]; such advances include changes in applied potential [A27, S80], improvements in films and screens [H45, M66, V17], asymmetric [M67] and twin [M65] screen-film combinations, beam equalization systems [V18], and digital techniques such as storage phosphor (computed) radiography [H46, I29], image intensifier radiography [B65] and selenium drum detectors [C39, H47, L36]. Mobile x-ray units are used in hospitals for radiography on patients who cannot be moved from their beds. Such examinations are routinely performed in intensive therapy units [L34] and frequently in other wards; collectively, they may account for nearly one half of all chest radiographs in large hospitals [W7]. Reported doses from some different techniques in chest radiography are summarized in Table 20. Gonad doses are low (<0.03 mGy per exposure) when there is adequate beam collimation [L34, N36].

55. Fluoroscopy is widely used in some countries for conducting radiological examinations of the chest (see Table 12). Reported patient doses are summarized in Table 15. In general, the effective doses when using fluoroscopy are larger than those from radiographic or photofluorographic imaging of the chest.

(d) Dental radiography

56. Dental radiography is one of the most frequent types of radiological procedure, although the exposures to individual patients are low. The most common techniques involve intraoral non-screen films either to provide an image of the upper and lower teeth together (bitewing radiography) [C19] or to demonstrate full tooth structure, including pulp, root, and gum anatomy (periapical radiography). Digital subtraction radiography techniques are also used in longitudinal studies [R14]. Alternatively, narrow-beam rotational tomography is used to view the teeth and jaw bones in a single image; such panoramic radiography uses an external film in a cassette with intensifying screens and an x-ray tube that rotates around the head to provide a tomographic image of the whole mouth [G26]. Data on frequencies and effective doses in dental radiology reported for various countries are presented in Table 21. Entrance surface doses are summarized in Table 22.

57. Notwithstanding the relatively low levels of individual exposure from dental radiology, the dose to the patient can be significantly influenced by the equipment and technique used and the quality assurance measures in place [C13, N3]. Some typical values of effective dose per dental x-ray examination for a range of exposure conditions are shown in Table 23; these data indicate broad variations by factors of 8 and 2 for changes in technique for intraoral and panoral procedures, respectively. The effective dose from intraoral radiography is less dependent on the radiation quality of the x-ray beam than is the case for general radiography [K42]. Optimized techniques of periapical radiography have been shown from measurements in an anthropomorphic phantom to result in entrance doses of 0.5–1.3 mGy and effective doses of 1.1–3.3 μSv per exposure [L17]. In contrast, the mean entrance surface dose for conventional dental x-ray examinations in Romania apparently rose by about 250% between 1980 (10.7 mGy) and 1990 (27.5 mGy), with a concomitant tenfold increase in effective dose (0.01 mSv to 0.11 mSv); this trend was attributed largely to shortcomings in x-ray technology [D9].

58. The planning of dental implant surgery often requires tomographic imaging to evaluate the dimensions of the potential implant sites and the location of anatomical structures. Both conventional tomography and CT are routinely employed in dento-maxillofacial radiography [E9]. Using hypocycloidal or spiral conventional tomography, the absorbed doses to radiosensitive organs are below 0.2 mGy. Doses from CT can be considerably higher, with, for example, maximum doses of 38 mGy and 31 mGy being measured at the skin surface and the parotid gland, respectively [E9], although methods for reduced doses from helical CT have also been demonstrated [D32, D39]. The dose from a new volumetric CT scanner, developed specifically for dental imaging, is reported to be approximately one sixth of that from traditional spiral CT [M27]. The use of a dedicated multimodal dental imaging system has also been shown to involve lower doses than alternative CT techniques [L26]. On the basis of measurements in a human phantom, estimates of effective dose for such complex film tomography range from <1 μSv to 30 μSv, depending on the anatomical location of the imaging plane and the collimation option used [F13]; similar measurements for panoramic radiography gave an effective dose of 26 μSv.

59. Orthodontic analysis in the diagnosis and treatment of malocclusion disorders uses the standard imaging technique of cephalometry to generate reproducible images of the skull, dentition, and facial profile soft tissues. Such cephalometric radiographs involve lateral views of the skull from a fixed distance. The doses produced at particular anatomical sites in the head by different experimental techniques have been shown to vary by up to an order of magnitude [T14].

60. Direct digital imaging systems, which can provide adequate image quality at significantly reduced doses in comparison to conventional techniques, are becoming increasingly available for both intraoral [B28] and panoral [N4] radiography. Doses associated with charge coupled devices (CCDs) and computed radiography systems (photo-stimulable phosphor luminescence technology) have been reported to be up to approximately 50% and 80% lower, respectively, than those associated with conventional techniques.

(e) Mammography

61. The number of countries with mammography screening programmes has been increasing, and this trend is likely to continue [U3]. Initially, routine screening was generally not carried out for women under the age of 50 [B68, D8], although younger women have now been included in some countries. National screening programmes are broadly characterized by good quality control and standardization of practice. The doses to patients from mammography reported for various countries are summarized in Table 24. Periodic surveys in some countries have demonstrated reductions in dose over the last decade due to improvements in quality control and changes in technique (see, for example, [C5, C40, F10, M7]); in other countries [L38, S82], doses have increased due to trends for higher film optical densities and the use of grids for improved image quality [R34, W51]. There is no general consensus in Europe concerning the best way for balancing dose and image quality [V19, Z21].

62. Mammography is generally carried out using dedicated, special x-ray equipment that employs relatively low applied potentials (25–30 kV) and tubes with molybdenum anode/filter combinations; such equipment is sometimes mounted in vehicles to provide mobile units for screening programmes [D41]. The mean dose to the glandular tissue is affected by the size and composition of the breast, with the former varying both within and between populations and the latter throughout a woman's life [E13]. Standard phantoms and models of the breast are generally adopted to facilitate comparisons of practice, although surveys of doses to individual patients are increasingly also being conducted (see Table 24). Recent

innovations in equipment that allow a choice of different anode/filter materials (such as rhodium) and automatic selection of applied potential offer advantages in dose and image quality, particularly for women with relatively thick breasts on compression [T20, Y14, Y15].

63. Digital imaging techniques are being developed that potentially could provide lower doses than at present, while also allowing improvements in image quality, although their improper application could result in higher doses [A28, C41, C42, G16, K6, K45, K46, K48, N38, P1]. Other developments include the use of niobium filtration [C43], equalization techniques [P29, S84], phase contrast imaging [A36, I32, K51], a laser-based micro-focused x-ray source [K47], and synchrotron radiation [A29, B13, J5]. MRI is also being developed for mammography [K1, W52]. However, in the short term at least, conventional film-screen mammography is likely to be the primary breast imaging modality, supplemented by ultrasound techniques [S18].

(f) *In utero* exposures

64. X-ray examinations on pregnant patients may also expose the fetus [D42]. For this reason, many such types of procedure are not carried out routinely without there being overriding clinical indications, although there may also be inadvertent fetal exposure from examinations conducted in the very early stages of pregnancy [E14, S85]. Precise estimates of fetal dose may require special techniques, although uterus dose is often assumed as a surrogate [A30, M68, O16, O17]. Typical doses to the uterus from common types of x-ray procedure are summarized in Table 25 [W30] (see also various other sources of data, including, for example [O15, S85]). The wide range of doses reported is due to differences in equipment and technique. For example, one study of maximum absorbed dose to an embryo from intravenous urography demonstrated a range between hospitals of 5.8 to 35 mGy [D25].

65. X rays have also been used for more than 50 years to assess the dimensions of the maternal pelvis in pregnancy. Such pelvimetry is usually performed in the late stages of pregnancy if cephalopelvic disproportion or breech presentation is suspected. In the United Kingdom, for example, pelvimetry is typically performed in connection with 1%–4% of all deliveries in an obstetric department, with over two thirds of the centres in a national survey reporting its use as being either static or decreasing [M29]. A range of techniques are employed, including conventional plain film radiography using a grid or air-gap technique (generally involving a single erect lateral projection, but with up to three films for postnatal investigations), CT (generally a single lateral scan projection radiograph, but with antero-posterior (AP) projection and axial slices also being used), and digital radiography; MRI pelvimetry is also under investigation. Differences in x-ray technique lead to wide variations in the resulting dose to the fetus [T21]. Measurements at 20 centres in the United Kingdom with an anthropomorphic phantom of a pregnant woman at full term revealed mean fetal doses varying by a factor of up to about 40 [B47]. Those from conventional pelvimetry were in the range 0.15–0.75 mGy, with doses from CT pelvimetry spanning 0.05–0.35 mGy. Conventional pelvimetry (erect lateral projection) gave, on average, four times the dose from CT pelvimetry (lateral scan projection radiographs), although the use of an air gap technique resulted in doses that were comparable to those with CT. Digital pelvimetry using storage phosphor plate technology (computed radiography) can be conducted with doses that are about 50% of those from high sensitivity screen-film systems [H50, K52]. Digital fluorography has also successfully been utilized in pelvimetry, where it allows a tenfold reduction in entrance surface dose compared with conventional techniques [W10], although the potential for lower fetal doses with this technique depends on the ease of patient positioning [B47].

(g) Bone densitometry

66. Assessment of the mineral content of bones by densitometry is used in the diagnosis and management of patients with metabolic bone disease. Over the last 30 years, a number of non-invasive radiological techniques have been developed for performing quantitative measurements on bone [G8, G41, G42, S23, S28, S87, W13]. Notwithstanding the early use of quantitative measurements based on conventional radiography [J14], the first commercially available specialist technique was that of single-photon absorptiometry (SPA), in which transmission through the patient of a scanning pencil beam from a radionuclide source is measured with a detector. Such measurements on bones in the arm or heel typically involve surface doses of 50 μGy and effective doses of <1 μSv [G5]. Truscott et al. [T3] have developed a portable system for measuring bone mineral density in the pre-term neonatal forearm, with an absorbed dose to the skin of 6 μGy.

67. Broadly similar levels of dose are achieved when the radionuclide source used in SPA is replaced by an x-ray tube, as in the technique of single photon x-ray absorptiometry (SXA). Measurements at more clinically relevant sites were made possible with the development of dual photon absorptiometry (DPA), although since 1988 this technique has largely been superseded by dual photon x-ray absorptiometry (DXA). Depending on the manufacturer, the dual energy x-ray beam required for DXA is generated either by rapidly switching the applied potential between 70 kV and 140 kV or by using an energy-selective rare earth filter [B4]; flash pulses from a portable, field emission x-ray tube have also been investigated [S86]. First-generation DXA scanners used a pencil beam, but the subsequent introduction of fan beams has allowed more rapid scanning. The dose to the patient depends on the precision of the measurement, as well as the site of investigation, which is commonly the spine, femur, hip, or whole body. Effective doses are typically 0.1–8 μSv per examination, with an entrance dose of 2–1,400 μGy [B69, G5, H12, K7, L9, N11, N12, N39]. The latest DXA scanners with fan beams provide improved images with a near diagnostic radiographic quality, although the patient dose is somewhat increased (entrance surface dose of about 900 μGy

and effective dose of 7–75 μSv [N12, N39]). Doses have also been reported for DXA measurements on a 5 year old child: an entrance surface dose of 6.0 μGy and an effective dose of 0.28 μSv for PA scans of the spine, and an entrance surface dose of 0.12 μGy and an effective dose of 0.03 μSv for total body scans [N40].

68. Experimental devices for bone densitometry have also been developed that are based on radiation scattering (Compton or Rayleigh) techniques, although such equipment is not in widespread use [M69, W53]. The absorbed dose over the volume of measurement is typically below 2 mGy with radionuclide sources [D12] and 0.1 mGy with a polychromatic x-ray source [S23].

69. A differential measurement of cortical and cancellous bone can be obtained from digital images provided by CT scanners using the techniques of quantitative computed tomography (QCT) [G5, P30]. Patient doses are relatively high, although they are critically dependent on the details of the method used. For measurements on the spine with a single energy technique, reported effective doses are 0.05–2.2 mSv and the surface doses between 10.4 mGy and 33.8 mGy; corresponding effective dose data with a dual energy technique range from 0.1 to 1 mSv [G5, H12, K7, N11, N39]. QCT measurements are also performed on the peripheral skeleton (pQCT) [L39], with an effective dose typically of about 3 μSv [G5].

70. Bone densitometry has an important role in the diagnosis of osteoporosis in high-risk groups and in the monitoring of treatment in particular patients, although the technique is not at present widely used in population-based screening for, say, low bone mass in perimenopausal women [C10]. DXA has become the most widely used technique. Variations in the levels of provision for DXA in different countries are indicated in Table 26. It has been estimated that clinical practice in the United Kingdom would ideally entail about 175 bone scans per 100,000 population per year. The annual collective dose from this enhanced level of examinations would typically be around 1 man Sv; by comparison, the total from all diagnostic examinations with x rays in the United Kingdom is about 20,000 man Sv.

71. DXA could become a tool for population screening. The estimated worldwide total of axial DXA scanners has increased steadily from over 6,000 in 1995 [L5] to 12,500 in 1998 [L40]; there are also over 9,000 peripheral x-ray systems [L40]. Notwithstanding such worldwide growth in the practice of bone densitometry, patient doses per examination are at the lower end of the exposure range normally encountered in diagnostic radiology. Accordingly, the contribution to collective dose from increased numbers of these procedures is still likely to remain insignificant.

(h) Paediatric radiology

72. Over the last decade, paediatric radiology has become internationally recognized as a subspeciality within diagnostic radiology, with increasing numbers of specialized radiologists, departments, and imaging equipment. Examinations of children (aged 0–15 years) merit special consideration in view of the increased radiation risk [R35]; the increased risk for thyroid, skin, brain, and breast cancer arising from the exposure of children is discussed further in Annex I, "*Epidemiological evaluation of radiation-induced cancer*". Specific techniques are required for assessing organ and effective doses to paediatric patients (see Section II.B and, for example, [A31, A32, H16, H38, H51, H52, P32, V20, V21, Z22]). There is, however, a relative lack of information on the typical levels of dose for such examinations. A preliminary analysis based mainly on data from the United Kingdom suggests that effective doses to children from conventional (not digital) radiographic x-ray examinations are, in general, lower than those from conventional examinations of adults by factors of between 2 and 10, depending on the age group [W11]. For examinations of the chest, which are by far the most frequent procedure for children, doses are generally no less than about one half of those for adults, whereas doses for examinations of the head appear broadly independent of age. For complex examinations involving many radiographs and fluoroscopy, such as barium meals, effective doses to children are generally about 30%–60% of those for adults. However, doses to paediatric patients from CT may be similar, or even higher, than the relatively high levels observed for adults [H38]. Age-specific dose data for x-ray examinations in Poland indicate patterns similar to those described above [L7].

73. As part of the development of quality criteria for diagnostic radiographic images in paediatrics [P31], three surveys of entrance surface dose measurements were carried out in Europe between 1989 and 1995 for frequent x-ray examinations [K4]. The results of over 1,500 such measurements are summarized in Table 27. For chest and skull examinations, there is a remarkable similarity between the median values for the three age groups, with no distinct increase with age. In all cases, the distributions of dose were very wide. Other local surveys have demonstrated variations in practice [B70, C44, L41, O3] and reduced levels of dose attributable to the careful choice of equipment and technique [C45, K19, M30, M31, M32, S88]. The main factors influencing dose for radiographic procedures are the speed of the film-screen combination and the use of an antiscatter grid. The main factors for fluoroscopy are the use of a grid and the operating characteristics (dose rate level) of the image intensifier [T22]. Differences in practice have been reported between non-specialist and specialist paediatric imaging centres. The latter often delivered higher doses to younger children as a result of the widespread use of a grid; doses in fluoroscopy were significantly lower, however [K19]. Some examples of the doses achievable with best practice [C20] are given in Table 28.

74. Reduced doses have also been reported from the use of digital imaging techniques in paediatric radiography. Computed radiography has been used successfully at speeds (using the analogy of speed classification for film-

screen systems) corresponding to 600 for chests and 1,000 for other examinations on children [H22]. Since few departments in the United Kingdom appear to employ film-screen systems with speeds greater than 400, such practice with computed radiography is equivalent, on average, to dose reductions of at least 60% (or 30% for chests). Initial results with a novel digital x-ray device incorporating a multiwire chamber show that it could significantly reduce doses in paediatric imaging [K20]. The mean values of entrance surface dose measured on samples of children undergoing different types of radiograph were 0.08 mGy (AP spine), 0.07 mGy (PA spine), 0.13 mGy (LAT spine), and 0.06 mGy (pelvis); entrance surface doses for a conventional imaging system were higher by a factor of between 12 and 19.

75. Reductions have been reported in the frequency of x-ray examinations of the urinary system and skeletal surveys for malignant disease when radionuclide studies are integrated into strategies for paediatric imaging [G2]. For older children, the effective dose from intravenous urography (IVU) may be double the dose of about 1 mSv from the alternative diagnostic technique for renal investigation, ^{99m}Tc DMSA scintigraphy [S45].

D. ASSESSMENT OF GLOBAL PRACTICE

76. Table 29 shows some reported national average annual individual doses (per patient and per caput) and collective effective doses from diagnostic medical x-ray examinations. The assessment of global practice according to the model described in Section I.D, however, requires knowledge of the mean values, by health-care level, of the frequency and the dose for each type of diagnostic x-ray examination. Although the data in Table 12 provide robust estimates of the total numbers of examinations per 1,000 population within health-care levels I and II, the values for the individual types of examination have had to be averaged over different populations due to the lack of comprehensive information for all countries listed and so do not represent a self-consistent set of data. Estimates of the relative frequencies by type of examination have therefore been made using selected national data for each health-care level. When appropriately scaled and combined with typical values of effective dose per examination, these frequencies lead to the estimates of annual collective doses for 1991–1996 shown in Table 30; the limited data available for health-care levels III and IV have been pooled so as to provide more reliable estimates for a combined population. Analyses are presented separately for both medical and dental x-ray examinations. The rounded values of effective dose for each examination category are either based on the data in Table 15 or, particularly in the case of health-care levels III–IV, are estimates in the absence of more specific data. Derived average effective doses per examination and per caput are also shown. The percentage contributions to annual frequency and collective dose due to the various types of diagnostic medical x-ray examination are analysed by health-care level in Table 31. The uncertainties inherent in the estimates of mean frequencies and doses provided by the global model are difficult to quantify, but will be significant, particularly when extrapolations have been made on the basis of small samples of data.

77. According to the model developed, the global annual frequencies and doses assessed for 1991–1996 are dominated by the national practices in health-care level I; about 80% of the estimated global collective dose from medical x rays arises from examinations conducted in these particular countries, which together account for about one-quarter of the world population. The most important examinations in terms of the overall frequency of medical x rays are those of the chest and the limbs and joints, whereas the global collective dose is dominated by the more complex, but less frequent, procedures such as CT and examinations of the gastrointestinal tract. Significant differences are also apparent between the mean frequencies and doses for the different health-care levels. For example, the contributions from CT are markedly less for health-care levels II–IV relative to level I, and chest fluoroscopy appears particularly important for health-care level II due to its very high utilization for the large population of China. Practice with dental x rays has been assessed to be considerably smaller than that from medical x rays; the global frequency and collective dose are less than the corresponding values for medical x rays by factors of more than 3 and 100, respectively.

E. TRENDS IN DIAGNOSTIC RADIOLOGY

78. Trends in the global use of medical x rays are summarized in Figure IV in terms of increases, relative to the previous assessment for 1985–1990 [U3], in some key indicators of annual practice; small changes are unlikely to be significant in view of sampling differences and uncertainties in the estimated values. Whereas there has been an increase in global population by about 10% between studies, the estimated global total number of examinations has grown by about 20% and therefore the frequency per 1,000 population has increased by about 10%. The overall mean effective dose per examination has risen by about 20% and the annual collective effective dose by nearly 50%. Differences in the patterns of practice between the assessments for 1985–1990 and 1991–1996 are highlighted in Figure V, which illustrates the relative contributions by examination type to the global collective dose from medical x rays. Most notably, increases in contributions are apparent from CT, angiography and interventional procedures, with there being decreased contributions for examinations of the gastrointestinal tract and chest photofluorography. The global annual collective effective dose from dental x-ray examinations estimated for 1991–1996 is about 20% lower than the collective effective dose equivalent estimated for the previous assessment [U3]; the inherent differences in magnitude between these two dose quantities expected for dental exposures have already been

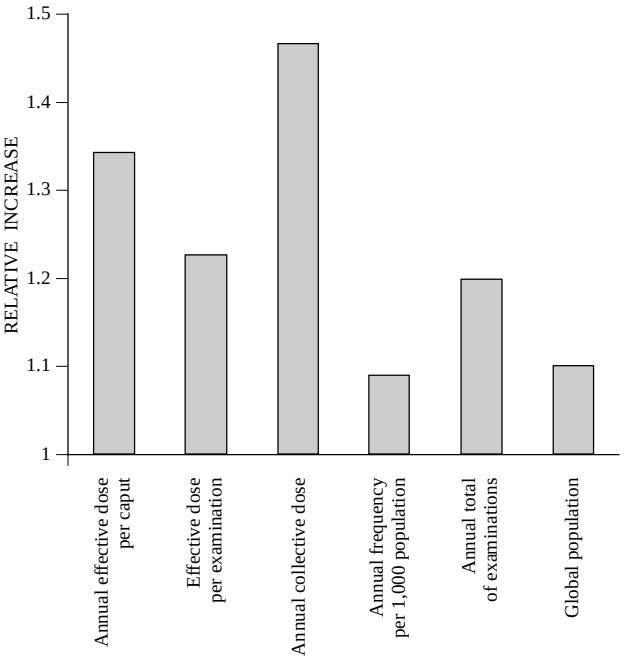

Figure IV. Temporal trends in global practice with medical x-ray examinations: average frequencies and doses for 1991-1996 relative to previous estimates for 1985-1990.

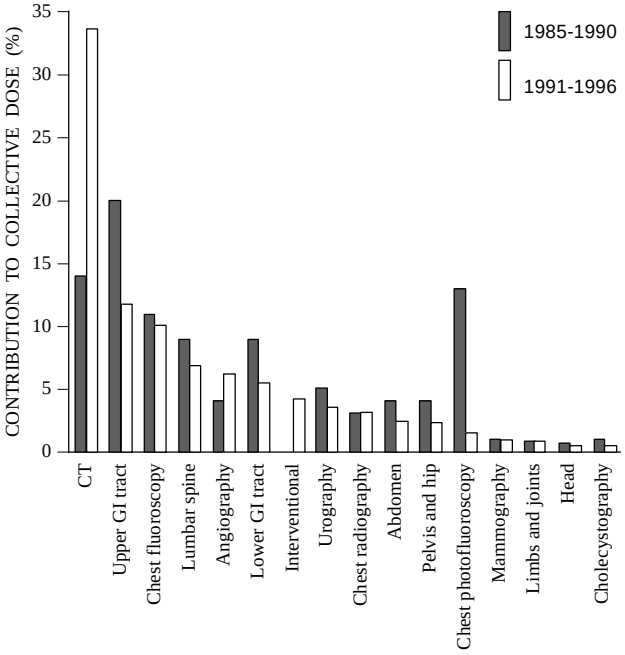

Figure V. Percentage contributions by examination type to global collective dose from medical x-ray examinations: comparison of data for 1955-1990 and 1991-1996.

noted (Section II.B). The present estimate of effective dose per caput is about 30% lower than the figure assessed previously for dental x rays. In light of the considerable variations in the reported national data concerning the distributions by age and sex of patients undergoing various types of diagnostic x-ray examination (Table 14), it is difficult to discern any specific trends in the mean values relative to previous data. The average levels of x-ray equipment per million population estimated for the various health-care levels and time periods are summarized in Table 7, although the significant differences that exist between individual countries of the same health-care level and the limited sample sizes should also be noted (Table 4). However, the analysis suggests a broad trend for reducing numbers of medical x-ray generators per million population in health-care level I and hence also in the world. There is an apparent increase in the average number of medical x-ray examinations per medical x-ray generator, with estimates of 2,500 for 1991–1996 and 2,100 for 1985–1990.

79. Overall trends in radiation exposures from diagnostic examinations with x rays are due to two kinds of change: changes in both the type and frequency of the procedures carried out, as determined by the prevailing patterns of disease and clinical practice; and changes in the associated levels of dose to individual patients for given procedures. Doses are influenced by the continuing advances in techniques for the production, detection, and control of radiation, including the development of alternative modalities for diagnosis, as well as by initiatives in quality assurance and patient protection [A34, H54, H55, R36, R37]. Trends in the frequencies of examinations and doses per examination are discussed further in the two Sections following.

1. Frequencies of examinations

80. Temporal trends in the annual frequencies of all diagnostic medical x-ray examinations per 1,000 population are summarized in Table 32. The present estimates of average total frequency for health-care levels I (920 per 1,000) and II (154 per 1,000) are larger than the previous values for 1985–1990 (890 and 120 per 1,000, respectively), although the averages for each time period have been made over different populations; any comparisons of data for health-care levels III and IV are less reliable owing to the limited sample sizes involved. Notwithstanding these overall trends in average frequency for the different health-care levels of the global model, national frequencies have increased in some countries and decreased in others between 1985–1990 and 1991–1996; some specific examples are given below. Temporal trends in the average annual numbers of different types of diagnostic medical x-ray examination per 1,000 population by health-care level are summarized in Table 33. The annual frequencies of diagnostic dental x-ray examinations per 1,000 population for different countries and time periods are summarized in Table 34, together with the average values for each health-care level.

81. Increases in the annual total numbers of examinations and frequencies per 1,000 population have been reported for some countries, accompanied also by significant changes in the patterns of practice for individual types of procedure. For example, in the Czech Republic, the annual number of medical x-ray examinations rose from 8,100,000 in 1990 to 9,150,000 in 1994, with particularly large increases observed for CT and mammography due to the installation of new equipment and also some changes in the system of health

insurance. In Cyprus, the annual frequency of medical x-ray examinations rose steadily from 794 per 1,000 population in 1990 to 1,021 per 1,000 in 1995. In Poland, the annual number of x-ray examinations per 1,000 population rose from 572 to 715 between 1986 and 1996 [S49]. Increases were observed for examinations of the spine, CT, photofluorography and mammography, with there being decreases for urography and examinations of the upper gastrointestinal tract due probably to an increased use of ultrasound. In Norway, the total frequency of radiological examinations increased from 641 to 710 per 1,000 inhabitants between 1983 and 1993, with the most significant trends being for increased numbers of CT examinations and, owing to the introduction of alternative procedures, reduced numbers of examinations of the gastrointestinal tract [O6]. In Malaysia, almost all examinations experienced increasing frequency from 1990 to 1994, with the exceptions of barium studies, cholecystography and urography owing to an increasing use of ultrasound and fibre-optic endoscopy [N26]. The most notable increases were observed for CT, cardiac procedures and mammography. Data for the United States indicate an estimated increase of between 30% and 60% in the numbers of radiological examinations in hospitals between 1980 and 1990, with CT being an important influence [M1].

82. Elsewhere, practice has remained more static or has shown some decreases. In Bulgaria, the annual frequency of medical x-ray examinations rose from 220 per 1,000 population in 1950 to a peak of 1,170 per 1,000 in 1980, before falling to a level of 560 per 1,000 in 1992; corresponding values of effective dose per caput were 0.4 mSv, 1.79 mSv and 0.72 mSv, respectively for these particular years. In Russia, the annual frequency of medical x-ray examinations rose from 1,340 per 1,000 population in 1980 to a rate of 1,560 per 1,000 in 1985, since when it has fallen to a level of 1,230 per 1,000 in 1997; corresponding values of effective dose per caput for these particular years were 1.26 mSv, 1.32 mSv and 0.80 mSv, respectively. However, the frequency of dental x-ray examinations in Russia rose steadily from 74 per 1,000 population in 1985 to 96 per 1,000 in 1997. In the Ukraine, the frequency of x-ray examinations has decreased from 948 per 1,000 population in 1987 to 600 per 1,000 population in 1994, with the effective dose per caput decreasing correspondingly by about a factor 2 [K18]; these reductions were due in particular to decreases in the numbers of examinations being performed in the regions contaminated by the accident at Chernobyl and in the utilization of the higher-dose fluoroscopic procedures. In Ghana, estimates of the annual frequency of x-ray examinations during the period 1990 to 1996 ranged from 6 to 11 per 1,000 population, with there being no simple pattern [S38]. In Germany, the increase in the annual frequency of x-ray procedures between 1988 and 1992 has been slight overall, with increasing practice in CT, angiography, and interventional radiology offsetting a marked decrease in examinations of the gastrointestinal, biliary, and urinary tracts [A2]. The frequency of medical x-ray examinations has also remained fairly constant in the United Kingdom between 1983 and 1993, although the frequency of dental x-ray examinations has increased by over 30% [T15]. Large increases were also reported for CT, mammography, angiography and interventional procedures, with substantial decreases apparent for examinations that have been partially replaced by endoscopy (barium meals) and ultrasound (biliary and urinary systems). In contrast, the overall frequency of medical (excluding dental) x-ray examinations in Romania decreased by about 20% between 1980 and 1990, with the somewhat larger decreases (over 30%) for fluoroscopy and photofluorography being offset by an increase of over 20% for radiography [D1]; a subsequent analysis of all types of x-ray examination during 1990–1995 has suggested a fairly static total annual frequency (495 versus 511 per 1,000 population), although there have been further reductions in collective dose [D28]. In South Africa, the overall annual frequency of x-ray examinations (excluding mass miniature and dental) in 1990 was reported to be 180 per 1,000 population, although marked differences were observed between race groups, with rates of 67 per 1,000 for blacks, 110 for coloureds, 230 for Asians, and 460 for whites [M22]. In Canada, variations in the frequency of medical x-ray examinations between the different provinces ranged from 708 per 1,000 population to 1,043 per 1,000, with the national mean value being 892 per 1,000 [A15].

83. Developments in imaging technology, particularly those involving non-ionizing radiation, will have a significant influence on the practice of radiology and on the medical exposure of populations. Transfer of technology is likely to be most rapid in developed countries, categorized as health-care level I. MRI is becoming the imaging modality of choice for many areas of anatomical examination, although its wide-scale adoption was initially hampered by relatively long imaging times and high equipment cost [Z1]. The number of

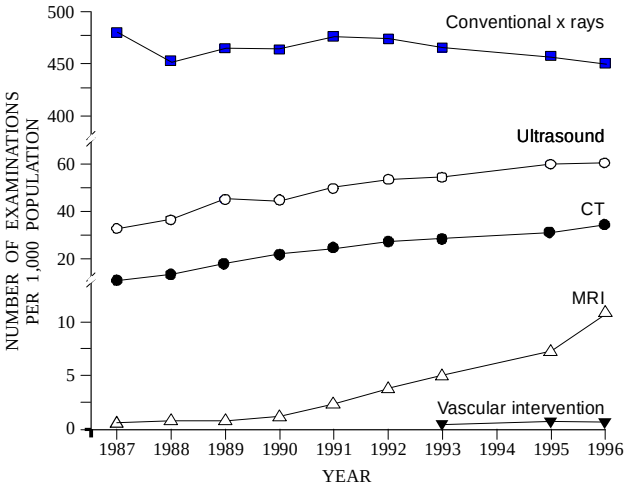

Figure VI. Trends in diagnostic radiology practice in the Netherlands [B89].

MRI studies worldwide grew from 6 million in 1989 to 18 million in 1995, with the total number of installed MRI systems having risen from 2,800 to 9,400 over this period [D23]. In contrast to MRI, ultrasound represents a relatively cheap, portable, and increasingly sophisticated form of imaging [W1]. Fibre-optic endoscopes allow direct visualiza-

tion of the gastrointestinal tract and not only complement but also replace some x-ray examinations [W2]. For example, surveys in the United Kingdom for one particular region (population 4.7 million) from 1986 to 1992 showed a steady increase in the annual frequency of endoscopies (upper gastrointestinal endoscopies and colonoscopies), from 8.4 to 10.0 procedures per 1,000 population, whereas there was a corresponding decline in barium studies (meals and enemas), from 12.9 to 10.1 procedures per 1,000 population [S36]. The trends in diagnostic radiology practice in the Netherlands between 1987 and 1996 are summarized in Figure VI [B89]; although the number of conventional x-ray examinations per 1,000 population has remained fairly constant, there have been increases in practice with CT, MRI and ultrasound.

84. Economic growth in South-East Asia is allowing significant improvements in general health care, and basic x-ray services are becoming available in most rural areas [M2]. Disease patterns in urban centres are becoming similar to those in Europe and North America, although a shortage of staff and a lack of standardization in training remain areas of concern in this part of the world.

2. Doses per examination

85. The average values of effective dose per examination derived from surveys by UNSCEAR are summarized in Table 35 by type of examination, health-care level and time period. Any analysis for trends is hampered by the averaging of doses over different populations and the uncertainties in the data. However, there are perhaps broad suggestions for reductions in typical dose with time for some radiographic examinations, such as pelvis and hip, and head, and for an increase in the dose per CT procedure between 1980–90 and 1991–1996. Overall, the estimate of 1.2 mSv for the global mean effective dose per medical x-ray examination during 1991–1996 (Table 30) is larger than the corresponding value of 1.0 mSv estimated for 1985–1990. This trend is likely to be due to the increasing use of complex and higher dose imaging procedures, particularly CT, in developed countries.

86. There are continuing developments in equipment and techniques for imaging [S90]. Film technology continues to advance, focusing on grain and emulsion structure in both the film and intensifying screen and on better spectral matching of the screen-film combination [F22, S1]. Conventional film images of high quality can be obtained with comparatively low patient doses, although there are still large differences in image quality for similar speed systems, depending on the manufacturer and on the screen-film combination [G1]. Digital radiological techniques offer the potential for improved image quality, although this is in general at the expense of higher patient doses. The impact of introducing such equipment depends somewhat on the choice of exposure settings and the techniques in use [K55]. For example, digital fluoroscopic systems were shown in one particular analysis to result in significantly lower levels of dose-area product during barium studies compared with non-digital systems: 7.8 Gy cm^2 and 24.2 Gy cm^2, respectively, for meals, and 13.9 Gy cm^2 and 25.3 Gy cm^2, respectively, for enemas [B14]. A second study, however, reported similar or even higher levels of dose from digital compared with conventional equipment (4.9 Gy cm^2 and 3.8 Gy cm^2, respectively, for meals and 16.7 Gy cm^2 and 20 Gy cm^2 for enemas), owing to increased levels of exposure during the fluoroscopic part of such examinations [H10].

87. For digital radiography systems, exposure can be preselected in a broad range so that patient dose can be adapted to the diagnostic problem and the image quality necessary. Photostimulable phosphor computed radiography offers the important advantages of high imaging efficiency over a wide exposure range and the presentation of images at consistent display levels independent of exposure levels [B71, F21]. The greater reliability of the image reproduction can lead to a reduction in the numbers of repeat films needed because of incorrect exposure [C1, P33, W55]. Reduction of patient dose per image is in general limited by considerations of image quality (signal to noise ratio), although lower doses have been reported for particular applications of computed radiography compared with doses from conventional techniques [J15, S89,W8].

88. For digital fluorography, spatial resolution is comparable to that with the 100 mm film technique, although lower than that for full-size, film-screen radiography. Image-intensifier-TV-based digital systems were shown in one study to reduce patient effective dose during examination of the abdomen by factors of at least 5 for a given projection when compared with conventional medium-fast film-screen combinations [M3]. In digital subtraction vascular imaging, the input dose to the image intensifier can vary significantly (typically 5–20 μGy per frame) depending on the particular settings selected [S3]; this dose is considerably higher than for modern digital fluorography (typically 0.5–1.5 μGy per frame) or for standard radiography with a fast (400 speed) film-screen combination (typically less than 5 μGy per radiograph). Accordingly, there is a potential for high patient doses in DSA as a result of the capability for rapid acquisition of images and the frequent use of long series of images for subtraction.

89. The introduction of digital imaging leads to significant changes in operational practices in radiology departments [C46, D43, K53, L42, V22]. The use of improper technique could result in higher patient doses. The increasing adoption of digital technology provides opportunities for advances in the post-processing of images, computer-aided diagnosis, and medical image management within and between hospitals using PACS systems [S91]. Such systems will allow better monitoring of radiology practice and help reduce patient exposures from the loss of films [H1, W56]. Initial developments came in the United States and Japan, but both large- and small-scale projects are now under way in European radiology departments [S4]. The transmission of digital radiographic images for remote consultation (teleradiology) promises to enhance practice in radiology, particularly for facilities at which services are otherwise deficient [L12,

W54]. However, the increasing utilization of digital imaging technology in developed countries, particularly CT and advances such as helical and dynamic CT scanning, is likely to result in further increases in the global average dose per examination.

90. Notwithstanding the proliferation of increasingly complex x-ray technology in developed countries, WHO has since the 1970s concentrated on developing design criteria for equipment to provide basic radiography, so as to lessen the inequity in imaging services around the world. The most recent version is known as the WHO Imaging System-Radiography (WHIS-RAD) [W12]. WHO-specified equipment is currently produced by several leading manufacturers, and by 1995 about 1,000 units had been installed in 60 countries. However, health services have failed to adopt the system to the degree that had been expected, despite its ease of use; there were, for example, only 39 units operating in nine countries of the Americas in 1997 [B33].

91. Novel digital x-ray imaging systems that employ improved detector technology and offer potential reductions in patient dose by up to two orders of magnitude in comparison with film-screen systems are under development [A35, L43, Y4]. These devices employ various approaches based on phosphor x-ray converters, where light quanta are produced as an intermediate stage, as well as direct x-ray-to-charge conversion materials such as gases and, using thin-film transistor and charge-coupled device (CCD) technologies, zinc cadmium telluride, amorphous selenium, and amorphous silicon [A33, C47, H53, M70, R38]. Self-scanned flat-panel detectors could in principle provide high-quality radiographic, fluoroscopic, or fluorographic images [S92, Z23]. In addition to such large-area devices, trials are in progress of a prototype low-dose imaging system based on a scanning beam geometry [S2].

92. More speculative developments in imaging are under investigation, including the use of synchrotron radiation [C48, K56, L44, M5], phase-contrast imaging using polychromatic hard x rays [W6], time-gated imaging using x rays from a laser-produced plasma [G44], and a compact radiological source based on electron cyclotron resonance magnetic mirror discharge [B2]. Also, the recent availability of large-array biomagnetometer systems is facilitating the development of techniques of magnetic source imaging, in which magnetoencephalography is combined with MRI to map brain activity for the purposes of guiding neurosurgical interventional procedures [G15]. It has been argued, however, that radiology practice is on balance likely to be more affected in the medium term by the maturing of existing technologies than by the innovative modalities under development [Y1].

3. Quality assurance and patient protection initiatives

93. Measures that facilitate the achievement and maintenance of good practice in diagnostic radiology will have some influence on the frequency of examinations and levels of patient dose [T16]. In general, such initiatives can be expected to decrease doses per examination and per caput doses worldwide, owing to reductions in repeated and unnecessary exposures [D44, K54, M71]. Among the topics of relevance will be the implementation of quality assurance measures in radiology departments, including accreditation under formal quality systems [I1] and audits of practice [G43, M72, V23, W58, W59]; the training and education of persons involved with medical radiation, including clinicians, technicians, physicists, and administrators [I2]; the promulgation of basic recommendations on patient protection [I3, I5, I17]; and guidance on the rational and effective use of imaging [H30, W3, W4, W5].

94. Several studies have highlighted the problem of unnecessary exposures. An analysis in the United Kingdom, for example, suggested that at least 20% of examinations were clinically unhelpful to patient management and, without any clear justification, should not have been performed [N2]. Guidelines [C49, R1] for the appropriate use of diagnostic radiology have been found to reduce selectively the rates of referral by primary care physicians (general practitioners) [R2]. Clinical audit, which is a retrospective analysis of performance that is closely linked to the mainly prospective process of quality assurance, is likely to play an increasingly important role in the control of radiology. In Romania, a study of radiology practice at a sample of 130 hospitals in 1995 observed that about 23% of the radiographs produced were of no diagnostic utility; this rate equates, on a national scale, to a total of 2 million such radiographs [D6]. Over 50% of darkrooms in the study were found to have excessive illumination.

95. Dose reductions attributable to the influence of patient protection measures have been reported in several large studies. A review in 1995 of national dose data in the United Kingdom revealed an average 30% reduction over a 10-year period in the mean levels of entrance surface dose and dose-area product for common types of radiograph and x-ray examination [H11, W57]. The main identifiable reason for this dose reduction was the more extensive use of faster film-screen combinations, facilitated by the coherent combination of a national protocol for patient dose measurements and systematic advice on patient protection, including national reference dose levels [N41, S6]. Fewer than 10% of hospitals exceeded the national reference doses in 1995, compared with 25% in 1985. Such reductions in the collective dose from conventional x-ray examinations in the United Kingdom will, however, have been offset by the much increased use of CT [S10]. Practice in CT can be expected to be influenced in due course by the development of quality criteria for CT examinations, which include reference dose levels [E4]. The applicability of similar European quality criteria to radiographic images of adult patients has been assessed widely in surveys involving some 3,000 dose and image quality measurements in about 100 hospitals [C6].

Even as these surveys show the persistence of wide variations in performance, they provide clear evidence that higher doses prevailed when there was little or no compliance with recommended techniques [M11].

96. Significant dose reductions have also been demonstrated over a 5-year period at a large teaching hospital in Madrid as the result of a systematic programme for the optimization of patient protection, which included implementation of patient dosimetry and quality control [V1]; in particular, between 1986 and 1990 effective doses for studies of the gastrointestinal tract were reduced by about 50% as a result of replacing deficient fluoroscopic equipment (from 10.7 mSv to 4.9 mSv for barium meals and from 9.4 mSv to 6.8 mSv for barium enemas), while doses from examinations of the spine fell by about 40% owing to changes in film cassettes and tube filtration (from 0.31 mSv to 0.18 mSv for cervical spine and from 2.2 mSv to 1.4 mSv for lumbar spine). In contrast, there were increases over this period in the mean doses per examination from CT (from 5.7 mSv to 6.5 mSv) and angiography (from 12 mSv to 13 mSv) and increases by a factor of 2 in the contributions from these procedures to total collective dose (with 25% due to CT and 17% from angiography in 1990).

97. A pilot international programme on radiation doses in diagnostic radiology, which involved two series of measurements in seven countries on three continents, achieved considerable reductions in dose, without deterioration of diagnostic information, by the application of simple and inexpensive methods [I4, O8, O18]. Average reductions of about 50% in entrance surface dose were reported following increases in tube filtration, applied potential and film-screen speed. These methods led to significant improvements between surveys in the percentage of x-ray rooms complying with reference dose values suggested by the European Commission [C6]: initial and final levels of compliance were 20% and 75% for lumbar spine (PA), 29% and 36% for chest (PA), 75% and 100% for abdomen, and 0% and 100% for breast.

98. Dose reductions from changes in equipment or technique, without any significant effect on the diagnostic efficacy of examinations, have also been reported by numerous individual studies. These include, for example, the use of rare earth intensifying screens for radiography [G33, J4, S55], lower tube currents during fluoroscopy [S21], pulsed fluoroscopy [V12], review of grid usage in fluoroscopy [L30, S52], additional filtration [G30], and region-of-interest (ROI) radiologic imaging [G32, K25, M43, S59]. The latter involves placement, between the x-ray source and the patient, of a filter which attenuates the beam peripheral to the ROI. Reported dose reductions associated with the introduction of such filters are as follows: 70% in dose-area product during fluoroscopy [L1] and factors of 3–10 in skin dose during imaging in neurointerventional radiology [R5].

F. SUMMARY

99. The utilization of x rays for diagnosis in medicine varies significantly between countries (Tables 4, 8 and 12). Information on national practices that has been provided to the Committee by a sample of countries has been extrapolated to allow a broad assessment of global practice, although inevitably there may be significant uncertainties in many of the calculated results. On the basis of a global model in which countries are stratified into four health-care levels depending on the number of physicians relative to the size of population, the world annual total number of medical x-ray examinations for 1991–1996 is estimated to be about 1,900 million, corresponding to a frequency of 330 per 1,000 world population (Table 9); previous estimates of these quantities for 1985–1990 were 1,600 million and 300 per 1,000 population, respectively. The present global total of examinations is distributed amongst the different health-care levels of the model as follows: 74% in countries of level I (at a mean rate of 920 per 1,000 population), 25% in countries of level II (150 per 1,000 population) and 1% in countries of health-care levels III–IV (20 per 1,000 population). In addition to such medical x rays, there is also an estimated global annual total of about 520 million dental x-ray examinations, corresponding to a frequency of 90 per 1,000 world population; the assumed distribution between health-care levels is for over 90% to occur in level I and <0.1% in levels III–IV. Notwithstanding the estimated mean frequencies of examination for each health-care level quoted above, there are also significant variations in the national frequencies between countries in the same health-care level (Tables 32 and 34).

100. The estimated doses to the world population from diagnostic medical and dental x-ray examinations are summarized in Table 36. The global annual collective effective dose from medical x rays for 1991–1996 is estimated to be about 2,330,000 man Sv, equating to an average dose per caput of 0.4 mSv; previous estimates of these quantities for 1985–1990 were 1,600,000 man Sv and 0.3 mSv, respectively. The distribution of collective dose among the different health-care levels of the global model is presently as follows: 80% in countries of level I (giving a mean dose of 1.2 mSv per caput), 18% in countries of level II (corresponding to 0.14 mSv per caput) and 2% in countries of health-care levels III–IV (corresponding to 0.02 mSv per caput). Diagnostic dental x-ray examinations are estimated to provide a further annual collective dose to the world population of about 14,000 man Sv, equating to about 0.002 mSv per caput; these values are less than the corresponding estimates for 1985–1990 of 18,000 man Sv and 0.003 mSv per caput, although uncertainties in all these estimates are considerable and this apparent trend may not be real. Approximately 68% of the present global collective dose from dental x rays arises from countries in health-care level I, with contributions of about 31% and <1% from health-care levels II and III–IV, respectively.

101. The numbers of x-ray generators (excluding dental units) available for diagnostic radiology vary considerably between countries and the health-care levels of the global model (Table 4), with estimated averages per million population of 0.5, 0.2 and 0.02 for levels I, II and III–IV, respectively (Table 9). The estimated average annual number of medical x-ray examinations per medical x-ray generator is lower for countries of health-care levels III–IV (value of 1,100) than for those of level II (2,300) or level I (2,700). The estimated average values of annual collective dose per medical x-ray generator follow a similar global pattern: 1.2 man Sv per unit in levels III–IV, 2.0 man Sv per unit in level II, and 3.6 man Sv per unit in level I.

102. The estimated global mean effective dose per medical x-ray examination for 1991–1996 is 1.2 mSv (Table 30), which may be compared with the level of 1.0 mSv estimated for 1985–1990. However, the levels of dose to individual patients vary significantly between the different types of examination and also countries (Tables 15 and 16). The contributions to collective dose provided by the different categories of examination are summarized in Table 31 by health-care level. On a global scale, population exposure from medical x rays is now dominated by CT (which provides 34% of the annual collective dose), rather than examinations of the upper gastrointestinal tract (12%) which was estimated to be the most important procedure for 1985–1990 (Figure V). This new pattern also applies for countries of health-care level I, where the mean contribution from CT is presently 41%, although the dominant practices elsewhere are chest fluoroscopy in health-care level II (50% of collective dose) and examinations of the lower gastrointestinal tract in levels III–IV (34%), with CT providing contributions of only 5% and 2%, respectively.

III. DIAGNOSTIC ADMINISTRATIONS OF RADIOPHARMACEUTICALS

103. Administration of radionuclide preparations (radiopharmaceuticals) to patients, broadly referred to as nuclear medicine, is widely practiced throughout the world. The procedures are primarily intended for diagnostic purposes. Many of the diagnostic applications of radionuclides are conducted *in vitro* rather than *in vivo*. For example, about 100 million procedures with such material were performed in the United States in 1989, although only 10% of these involved the administration of radiopharmaceuticals directly to patients [N13]. The remaining 90% of practice comprised radioimmunoassay procedures, which use small amounts of radioactive material in the analysis of biological specimens such as blood and urine and do not give rise to the exposure of patients; these uses are not considered further in this review. Diagnostic *in vivo* examinations are discussed in this Section, and less-frequent therapeutic nuclear medicine procedures are considered in Chapter V.

A. TECHNIQUES

104. Whereas the broad aim in diagnostic radiology is the imaging of anatomy, the practice of nuclear medicine is more closely linked to the investigation of patho-physiological processes. In essence, radionuclides are used as a biological tracer by incorporating them into a pharmaceutical appropriate to the nature of an investigation; key technical advances are summarized in Table 37. Following administration of the radiopharmaceutical to the patient, the resulting biodistribution and localization is dictated by the pharmaceutical preparation used, with the radionuclide label providing the means of detection. Most procedures involve some type of measurement concerning the retention or excretion of the tracer so as to quantify organ or tissue function. Probe detectors can be used to measure uptake in particular organs such as the thyroid, whereas imaging is carried out using rectilinear scanners with single or double detectors or, more commonly, with a large field of view gamma camera.

105. Diagnostic techniques with radiopharmaceuticals are widely utilized in medicine; clinical applications include oncology [B80, M83, M84, R41, V26], cardiology [B81, P40, P41, Z26, Z27], neurology and psychiatry [E17], and endocrinology, as well as the investigation of infection and inflammation [N47, P38, P39] and various biological systems (musculo-skeletal, respiratory, gastrointestinal and genito-urinary) [M25, P8]. In oncology, for example, important roles for nuclear medicine include detecting unknown primary sites of cancer, differentiating between benign and malignant disease, staging the extent of disease (local, nodes and metastases), planning and assessing the response to therapy, and detecting recurrence [C18]. Alternatively, dilution techniques, based on the measurement of activity in samples of body fluids, can be used, for example, in haematology to assess plasma volume, red cell mass, total body water, extracellular fluid, and exchangeable electrolytes [P8]. The activities administered are determined by the diagnostic information required within the chosen period of the procedure [M86]. International [E10, E16, G48, I5] and national (for example, [A20, F25, M85]) guidance is available concerning the techniques and typical activities for common procedures.

106. In practice, a range of radionuclides are used in diagnostic nuclear medicine that meet the necessary requirements for effective and efficient imaging. All are produced artificially, using four principal routes of manufacture: cyclotron bombardment (producing, for example, ^{67}Ga, ^{111}In, ^{201}Tl, ^{57}Co, ^{123}I, ^{11}C, ^{15}O, ^{13}N, and ^{18}F); reactor irradiation (^{51}Cr, ^{75}Se, ^{59}Fe, ^{58}Co, ^{125}I, and ^{131}I, for example); fission products (yielding, for example, ^{131}I, ^{133}Xe and ^{90}Sr); and generators that provide secondary

decay products from longer-lived parent radionuclides. The most common example of the latter is the column generator incorporating ^{99}Mo for the provision of ^{99m}Tc which, because of its highly suitable physical characteristics for a wide range of applications, forms the basis for over 80% of the radiopharmaceuticals used in nuclear medicine. Most ^{99m}Tc generators utilize fission-produced ^{99}Mo, although techniques of neutron irradiation could provide a viable alternative source of this important parent radionuclide [B82, K61]. Other examples of generators include those incorporating ^{113}Sn (for the provision of ^{113m}In), ^{81}Rb (for ^{81m}Kr), and ^{68}Ge (for ^{68}Ga).

107. In addition to conventional planar imaging, techniques have also been developed to allow emission tomography which, like x-ray CT, can demonstrate internal structures or functional information from cross-sectional slices of the patient [I24]. Two basic modalities have evolved. The most common is that of single-photon emission computed tomography (SPECT). This utilizes conventional gamma-emitting radiopharmaceuticals and is often performed in combination with planar imaging. SPECT imaging requires a scanning system incorporating a circular array of detectors or, more often, a rotating gamma camera system with up to four detector heads. The second modality is the more specialized technique of positron emission tomography (PET). This is based on the simultaneous detection of the pairs of photons (511 keV) arising from positron annihilation and mostly uses the short-lived biologically active radionuclides ^{15}O, ^{11}C, ^{18}F, and ^{13}N. Dedicated PET scanners comprise a circular array of detectors, although PET imaging can also be performed using coincidence-adapted gamma camera systems [B83, J8, L50]. Quantitative functional tomographic imaging requires correction for the attenuation of photons by the patient, and this can be accomplished by transmission measurements made before, after, or during the emission scan, using an external radionuclide source [B39]. Such transmission measurements add little to the typical dose routinely received in clinical SPECT or PET; the additional dose is typically <0.1 mSv [A40, T12].

108. Radionuclides are also used for the intraoperative localization of tumours and lymph nodes using surgical nuclear probes and a range of radiopharmaceuticals [C53, P9, R13, S104, T13, W62]. Such practice has, for example, increased steadily in the United Kingdom since 1980, with a total of 68 surgical procedures being undertaken at 35 hospitals over a 15–year period [P10]. Probe detectors and mobile gamma cameras also allow bedside nuclear medicine investigation in the intensive-care unit [P11].

B. DOSIMETRY

109. The radiation doses to patients resulting from administrations of radiopharmaceuticals are determined by a range of physical and biological factors which include the amount and form of the radioactive material administered, the route of administration, the biokinetics and physiological fate of the radiopharmaceutical, and the decay scheme of the radionuclide [I35, M87, R42]. Absorbed doses to the various organs and tissues are generally estimated using the dosimetric formalism developed by the Medical Internal Radiation Dose Committee of the United States Society of Nuclear Medicine (MIRD) [L51, S105]. Broadly, this approach involves knowledge of the cumulative activities in each source organ, together with estimates and summation of the absorbed fractions of energy in every target organ from each source organ. Cumulative activities are derived on the basis of quantification of organ uptake in human studies using, for example, SPECT and PET imaging, or extrapolation from animal models [D47, L52, M87, S105]. Specific absorbed fractions are estimated by Monte Carlo calculations [L53, Z28] using anthropomorphic mathematical phantoms; values are available for standardized phantoms representing typical adult, paediatric and pregnant patients [S105, S106]; more realistic voxel phantoms are also being developed for use in internal dosimetry [J19, P42, Y18].

110. Coefficients derived using this methodology have been published that allow the estimation of organ and effective doses to adults and children from administered activities for a wide range of commonly used radiopharmaceuticals [I19, I37, I39]. Data are also available for some new radiopharmaceuticals (see, for example, [A41]) and for other computational techniques [J20, J21]. The administration of radiopharmaceuticals to patients also gives rise to the exposure of other population groups, such as breast-feeding infants [M88, M89], although these doses are not considered further in this review. The average doses to specific organs provided by conventional macroscopic dosimetry can grossly underestimate radiation exposures to individual cells [A42]. New methods of cellular dosimetry are being developed for assessing the risks associated with new pharmaceuticals that target specific cells and cellular components with short-range radiations, such as Auger electrons [B84, F24, H63].

111. Patient doses for common types of procedure are summarized principally in this review in terms of the administered activities for each radiopharmaceutical, although some typical values of effective dose are included and estimates of collective effective dose are used broadly to characterize overall practice.

C. ANALYSIS OF EXPOSURES

1. Frequency of examinations

112. The use of radiopharmaceuticals in medical diagnosis is less widespread than the use of x rays. There are large variations in practice from country to country, with nuclear medicine examinations not being performed at all in some smaller countries or LDCs. Annual numbers of diagnostic administrations of radiopharmaceuticals reported by different

countries for the years 1991–1996 are summarized in Table 38 by type of procedure and for all diagnostic practice. Data are presented in terms of numbers of administrations per 1,000 population, with some analysis by radionuclide and with countries grouped according to health-care level. These national figures were often estimated in quite different ways, and some particular qualifications to the data are given in the footnotes. The percentage contributions of each type of examination to total frequency are given in Table 39. Mean values of frequencies have been derived for each health-care level by averaging total numbers of procedures over total populations.

113. There are significant differences in the patterns of practice between countries, even for those within the same health-care level. National annual total frequencies vary by a factor of over 100 in the 36 countries in health-care level I utilizing nuclear medicine (0.5–65 examinations per 1,000 population); disregarding countries with zero practice, smaller variations exist in level II (0.6–2.1 examinations per 1,000 population in a sample of nine countries), level III (0.05–0.6 examinations per 1,000 population in a sample of three countries), and level IV (0.01–0.02 examinations per 1,000 population in a sample of two countries). The average total frequencies for levels II, III, and IV are smaller than the average for level I (about 19 examinations per 1,000 population) by factors of about 17, 70, and 1,000, respectively. These averages are less (by at least a factor of 50 in the case of level I) than the corresponding average use of x rays for diagnostic examinations at each level.

114. Notwithstanding differences between the individual countries, some general differences are apparent in the patterns of use between the broad health-care levels. For countries in level I, practice is dominated by bone scans, with significant contributions also from thyroid scans, cardiovascular studies, liver/spleen scans, and lung studies. In the United States, for example, 90% of practice in 1991 was accounted for by just 10 *in vivo* diagnostic procedures, although over 150 different types of nuclear medicine procedure were in use [N13]. For countries in levels II–IV, thyroid studies are the most important type of procedure. Temporal trends in the frequency of examinations are discussed in Section III.E.

2. Exposed populations

115. The distributions by age and sex of patients undergoing various types of diagnostic nuclear medicine procedure in 1991–1996 are presented in Table 40 for selected countries of the four health-care levels; additional information about some of these data is included in the footnotes. This analysis uses the same three broad ranges of patient age as were used for x-ray examinations, above, and in the UNSCEAR 1993 Report [U3]. Some country-to-country differences in age distribution are evident for each particular type of examination, even within the same health-care level. Previous analyses have suggested that diagnostic nuclear medicine is largely conducted on populations of patients who are in general older than those undergoing x-ray examinations and thus also older in comparison with whole populations [U3]. This conclusion is broadly supported by the present survey, although significant numbers of procedures, particularly renal and brain scans, are conducted on children. As for broad differences in practice between the health-care levels, there is for most types of procedure a shift towards the two younger age ranges for countries in levels II–IV compared with countries in level I. This is likely to reflect the known differences in national population age structures [U3].

116. Notwithstanding the preponderance of cardiovascular studies on males and thyroid studies on females, the distributions of nuclear medicine examinations between the sexes do not deviate greatly from the underlying patterns for whole populations, although some national variations are apparent in the data reported for particular types of procedure.

3. Doses

117. The typical activities administered in different countries for different types of diagnostic procedure in 1991–1996 are presented in Table 41. The average activities shown for key radiopharmaceuticals within each health-care level include weightings for the numbers of such administrations in each country. Some reported values of effective dose for common procedures, calculated from administered activities using standard dosimetric methods [I19, I37], are shown in Table 42. Typical effective doses from PET imaging are presented in Table 43, together with estimates of the corresponding mean doses to the uterus. Further data are given elsewhere concerning uterine doses for other nuclear medicine procedures (for example, [A20]) and doses to the embryo/fetus of pregnant patients [M90, R43, R44, S107]. In general, the typical effective doses from diagnostic nuclear medicine procedures span a similar range to those from diagnostic x-ray examinations.

118. Diagnostic procedures on children are conducted using levels of administered activity that are lower than the corresponding values for adult patients [E16, S41]. The administered activities are generally scaled according to body surface area or weight [A20]. When following the latter scheme, the resultant effective doses to children will in general be roughly the same as those to an adult. Examples of the effective doses to paediatric patients undergoing some common procedures are given in Table 44 [G47].

119. Abnormally high local tissue doses may result when there is partial or complete extravasation of the activity intended for intravenous administration [K64, P8]. For example, maximum local doses of 128 Gy (from 740 MBq ^{99m}Tc extravasated into 0.5 ml) and 378 Gy (74 MBq of ^{201}Tl) have been estimated on the assumption of no biological clearance, although doses in practice are likely to be substantially lower and no deterministic effects have been observed [B85, T24]. The absorbed doses to particular organs can be reduced through modifications to practice during some nuclear medicine procedures [I38].

D. ASSESSMENT OF GLOBAL PRACTICE

120. Table 45 shows some reported national average annual individual doses (per patient and per caput) and collective effective doses from diagnostic nuclear medicine procedures. In order to provide a systematic assessment of practice worldwide, national data from the UNSCEAR Survey of Medical Radiation Usage and Exposures have been combined on the basis of the global model of population described in Section I.D. The resulting annual frequencies estimated for common types of diagnostic nuclear medicine procedures are summarized in Table 46. These data have been derived with rounding by scaling the average relative frequencies observed for each health-care level (Table 39) by the average total frequencies per 1,000 population (Table 38); the mean procedure-specific frequencies in Table 38 can not be used directly since averaging has been carried out over different populations as a result of the incomplete sets of national data available. Table 46 also includes final estimates of collective dose on the basis of the doses per procedure shown, which are assumed broadly to be representative of practices for the different health-care levels. Derived average effective doses per procedure and per caput are also shown. The percentage contributions to annual frequency and collective dose due to the various types of diagnostic nuclear medicine procedure are analysed by health-care level in Table 47. The uncertainties inherent in the estimates of mean frequencies and doses provided by the global model are difficult to quantify, but will be significant, particularly when extrapolations have been made on the basis of small samples of data. In particular, uncertainties are likely in the frequencies of thyroid studies, where uptake scans will sometimes have been included in the national frequencies reported for thyroid scans, and in the effective doses from such studies, which can depend critically on the level of uptake in the thyroid. In general, the present analysis of patient exposures has been hampered by the variety of different radiopharmaceuticals in use for each type of procedure and the often incomplete data provided on national practices.

121. The present analysis suggests that the global annual frequencies and doses for diagnostic nuclear medicine in 1991–1996 are dominated by the national practices in health-care level I, with about 80% of the estimated global collective dose arising from procedures conducted in these particular countries. This finding is similar to that for diagnostic x-ray examinations, although the magnitudes of the two practices are quite different; the annual numbers of nuclear medicine procedures and their collective dose are less than the corresponding figures for medical x rays by factors of about 60 and 15, respectively. However, the overall mean dose per nuclear medicine procedure (4.6 mSv) is larger than that per medical x-ray examination (1.2 mSv).

122. The most important procedures in terms of both the overall frequency of nuclear medicine procedures and the global collective dose are bone scans, cardiovascular studies and thyroid studies, although significant differences are apparent between the practices assessed for the different health-care levels. In particular, thyroid studies are dominant in the lower health-care levels (III and IV).

E. TRENDS IN DIAGNOSTIC PRACTICE WITH RADIOPHARMACEUTICALS

1. Frequencies of examinations

123. Temporal trends in the annual frequencies of all diagnostic nuclear medicine procedures per 1,000 population are summarized in Table 48. The present estimates of average total frequency for health-care levels I (19 per 1,000) and II (1.1 per 1,000) are larger than the previous values for 1985–1990 (16 and 0.5 per 1,000, respectively), although the averages for each time period have been made over different populations; comparisons of data for health-care levels III and IV are less reliable owing to the limited sample sizes involved. Notwithstanding these overall trends in average frequency for the different health-care levels of the global model, national frequencies for individual countries have increased in some and decreased in others between 1985–1990 and 1991–1996; some specific examples are given below. Temporal trends in the average annual numbers of different types of diagnostic nuclear medicine procedures per 1,000 population by health-care level are summarized in Table 49.

124. The annual number of *in vivo* nuclear medicine examinations performed in hospitals in the United States increased by about 16%, from approximately 6.4 million to 7.4 million (30 per 1,000 population) between 1980 and 1990, slower than the projected growth rate of 8% per year for this period [M1]. This was mainly the result of the virtual disappearance of ^{99m}Tc pertechnetate brain scintigraphy and ^{99m}Tc sulphur colloid liver imaging, which have been replaced by other modalities such as CT and MRI, although cardiac and pulmonary procedures doubled their share of total studies. This pattern reflects different underlying trends. On the one hand there has been increasing use of alternative techniques providing high-contrast, high-resolution imaging as replacements for poorer-resolution nuclear medicine procedures for the detection and definition of pathological anatomy. On the other hand, pathophysiologically oriented nuclear medicine studies made significant progress as new radiopharmaceuticals (such as myocardial perfusion and cerebral blood flow agents), instrumentation (such as SPECT and PET), and computers and hardware (allowing, for example, renal function evaluation) became available [N13]. A further analysis of procedure volume in the United States showed virtually no increase on a national scale between 1992 and 1993 [T2]. The frequency of procedures in Canada is also likely to have remained fairly static between 1989 and 1993 [A15].

125. Similar trends for increases in overall practice have been observed elsewhere. For example, in the Slovak Republic, annual numbers of diagnostic procedures increased by an average of 2.5% per year between 1985 (4.7 per 1,000 population) and 1992 (5.6 per 1,000) [F8]. Comparison of

national data for the United Kingdom in 1982 and 1990 indicates an overall increase of 14% (to a level of 8 per 1,000 population) in the annual number of administrations (corresponding to an average of about 2% per year); a rise of 22% in imaging studies was, however, offset by a 30% decrease in the number of non-imaging investigations [E1]. There was less frequent use of radionuclides for brain and liver investigations owing to the greater availability of CT and ultrasound, whereas bone, lung, renal, and cardiac nuclear medicine studies increased in frequency. The estimated collective dose of 1,400 man Sv for 1990 represents an increase of about 50% over the estimate for 1982 [H3]. Practice in the United Kingdom increased by a further 15% between 1990 and 1993, probably due to a greater usage of myocardial perfusion and lung ventilation/ perfusion studies [E11, W63]. The trends observed in Germany for the different types of procedure have been broadly similar to those in the United Kingdom described above [K12]. In New Zealand, the frequency of diagnostic administrations rose by 12% between 1983 (7.5 per 1,000 population) and 1993 (8.4 per 1,000), with a large increase in bone scans offsetting reduced numbers of brain scans and liver/ spleen studies [L28]. Analyses of practices in Romania for 1990 and 1995 have shown a 12% increase in examination frequency and a 15% decrease in collective dose [I36]. A reduction in collective dose has also been observed in Finland between 1994 (220 man Sv) and 1997 (207 man Sv) as a result of reduced usage of ^{131}I and essentially constant total numbers of procedures [K59]. In Denmark, total numbers of diagnostic procedures rose from 76,433 in 1993 to 77,483 in 1995. Numbers of procedures have also risen in the Czech Republic, with totals of 236,819 in 1990 and 292,927 in 1994.

126. Somewhat greater increases in practice have been reported elsewhere. For example, in Australia there was a 50% increase in the frequency of nuclear medicine procedures between 1980 (8 per 1,000 population) and 1991 (12 per 1,000), corresponding to an average of 4.5% per year [C7]; the annual per caput effective dose from diagnostic procedures doubled, however, over this period (to 64 μSv). The number of radiopharmaceuticals in use grew to approximately 60, with ^{99m}Tc-, ^{201}Tl-, ^{67}Ga-, and ^{131}I-based materials dominating. In Cyprus, diagnostic practice rose from a total frequency of 2.7 procedures per 1,000 population in 1990 to 6.4 per 1,000 in 1996. In the Islamic Republic of Iran, the annual number of diagnostic nuclear medicine procedures increased by 42% over the years 1985–1989 (average annual rate of about 10.5% per year), to 1.9 per 1,000 population [M10]. In Russia, however, the frequency of nuclear medicine procedures fell from 15 per 1,000 population in 1990 to 13 per 1,000 in 1997.

2. Diagnostic practices

127. The role of nuclear medicine in patient care is being enhanced through advances in physics, computer sciences, medicinal chemistry, molecular biology and clinical care [B87, G50]. Important developments in radiopharmaceuticals are changing nuclear medicine practices [M91, P2]. The general trend is from diagnosis to prognosis, with the focus of research in pharmaceuticals moving from organs to cells, extracellular to intracellular processes, chemistry to biology and diagnosis to therapy [G49, I34]. In particular, there is increasing interest in the labelling of bioconjugates, such as antibodies, peptides and receptor-specific molecules, since these bioactive molecules offer the promise of selectively carrying radionuclides to specific sites for effective imaging (and therapy) [B86, P44]. Over 80% of the radiopharmaceuticals presently used in diagnostic nuclear medicine are based on ^{99m}Tc; this dominance is likely to continue through the development of new complexes for functional imaging. New ^{99m}Tc-labelled agents are able to replace a number of established agents on the basis of improved convenience, imaging, and dosimetry. There is, for example, increasing interest in ^{99m}Tc-based agents for myocardial perfusion imaging, brain perfusion, renal function, infection and inflammation, and tumour imaging [C54, D2]. Advances in cell labelling and the formulation of complex biological agents, such as monoclonal antibodies, are providing novel imaging applications using radioimmunoscintigraphy [K2]. However, ^{131}I is still widely used in many countries and has been the main reason for the observed higher effective doses per examination in developing countries compared with industrialized countries [U3]. The contribution of ^{131}I to the collective dose from diagnostic nuclear medicine practice varies considerably between countries: for example, about 90% for Romania [I6], 59% for the Islamic Republic of Iran [M10], 39% for the Slovak Republic [F8], 17% for Taiwan Province of China [L6], 10% for Finland [K59], 3% for the United Kingdom [H3], and 0.1% for Australia [C7].

128. Continuing developments in physics and instrumentation are improving the utility of nuclear medicine and are likely to influence patterns of practice, particularly in developed countries [K65, L54, S90]. The SPECT technique is becoming increasingly important in three-dimensional imaging, facilitated by the use of multiheaded camera systems, digital circuitry, and increased computer power [G3, T25]. Hybrid systems have also been developed to allow both SPECT and PET imaging (so-called coincidence-adapted cameras). The development of new compounds for labelling with short-lived positron-emitting radionuclides, such as ^{15}O, ^{11}C, ^{13}N, and ^{18}F, is creating an enormous potential for metabolic tracer imaging and physiological studies through the use of PET [G51, H64, J22, L55, L56, M92, S42, U16, W64]. Over 1,000 compounds have been labelled to study specific biochemical processes and physiologic function by PET [I34]. One estimate for the extent of PET in 1997 suggested a total of about 70 centres worldwide conducting studies at a rate of 4–6 patients per working day [A15]. There are now over 60 scanners installed in Germany and 30 in Japan; elsewhere the availability of PET is more limited, with, for example, Russia having 2 functioning scanners (with a further 2 in planning) [K16] and Argentina having the only PET scanner in Latin America [B88]. The expansion of PET on a larger scale will depend on the

availability in hospitals of cheaper equipment, appropriate radionuclides, and approved radiopharmaceuticals [F26, J23, W65]; technical developments can be expected to provide solutions to some of these problems [C8].

129. Significant reductions in patient dose during cardiac clinical investigations have been reported from the use of a novel camera employing a gas-filled multiwire chamber detector in combination with the short-lived radionuclide ^{178}Ta [L2]. This equipment is now commercially available and, in comparison with a conventional gamma camera, is claimed to involve dose levels that are 20 times lower than those for ^{99m}Tc and 200 times lower than those for ^{201}Tl.

F. SUMMARY

130. A wide variety of radiopharmaceuticals are administered diagnostically to patients to study tissue physiology and organ function. The utilization of diagnostic nuclear medicine varies significantly between countries (Tables 4, 8 and 38) and broad estimates of worldwide practice have been made from the limited national survey data available using a global model, although the uncertainties in this approach are likely to be significant. The world annual total number of procedures for 1991–1996 is estimated to be about 32.5 million, corresponding to a frequency of 5.6 per 1,000 world population (Table 9); previous estimates of these quantities for 1985–1990 were 24 million and 4.5 per 1,000 population, respectively. The present global total of procedures is distributed amongst the different health-care levels of the model as follows: 89% in countries of level I (at a mean rate of 19 per 1,000 population), 11% in countries of level II (1.1 per 1,000 population), and <1% collectively in countries of health-care levels III (0.3 per 1,000 population) and IV (0.02 per 1,000 population). Notwithstanding the estimated mean frequencies of examination for each health-care level quoted above, there are also significant variations in the national frequencies between countries in the same health-care level (Table 48).

131. The estimated doses to the world population from diagnostic nuclear medicine procedures are summarized in Table 50. The global annual collective effective dose for 1991–1996 is estimated to be about 150,000 man Sv, equating to an average dose per caput of 0.03 mSv; these estimates are similar to previous figures for 1985–1990 (160,000 man Sv and 0.03 mSv, respectively), despite the increase (by over 20%) in the frequency of procedures. The distribution of collective dose amongst the different health-care levels of the global model is presently as follows: 82% in countries of level I (giving a mean dose of 0.08 mSv per caput), 15% in countries of level II (corresponding to 0.008 mSv per caput), 2% in countries of health-care level III (corresponding to 0.006 mSv per caput), and 0.1% in countries of health-care level IV (corresponding to <0.001 mSv per caput). The contributions to collective dose from the different categories of procedure are summarized in Table 37. Globally, practice is dominated by bone scans, cardiovascular studies and thyroid studies, with the latter being particularly important in countries of the lower health-care levels (III and IV).

132. Overall, diagnostic practices with radiopharmaceuticals remain small in comparison with the use of x rays; the annual numbers of nuclear medicine procedures and their collective dose are only 2% and 6%, respectively, of the corresponding values for medical x rays. However, the mean dose per procedure is larger for nuclear medicine (4.6 mSv) than for medical x rays (1.2 mSv).

IV. TELETHERAPY AND BRACHYTHERAPY

133. Therapeutic uses of ionizing radiations are quite different in purpose from diagnostic radiological procedures. The aim in radiotherapy is to achieve cytotoxic levels of irradiation to well-defined target volumes of the patient, while as far as possible sparing the exposure of surrounding healthy tissues. Treatments generally involve multiple exposures (fractions) spaced over a period of time for maximum therapeutic effect. Radiotherapy is an important treatment modality for malignant disease, often in combination with surgery or chemotherapy [M77, S97, S98, W22]. The utilization of radiation treatment in oncology varies significantly between the different sites of disease and also countries. In the United States, for example, about 41% of all new patients with cancer in 1995 received radiation treatment, with specific rates for some particular sites/conditions being 80% for lung, 70% for breast, 30% for uterine cervix, 75% for uterine body and 1% for leukaemia [I23]. Corresponding radiotherapy utilization rates for cancer patients in Russia in 1995 were 23% (all cancer patients), 21% (lung cancer), 2% (breast cancer), 68% (uterine cervix), 7% (uterine body) and 3% (leukaemia) [C50]. Less commonly, radiation is also used in the treatment of benign disease [O19].

134. The clinical intention in radiotherapy may be either the eradication of cancer (curative treatment) or the relief of symptoms associated with it (palliative treatment [U14]). Most radiotherapy is carried out with radiation generators or encapsulated (sealed) radionuclide sources using the techniques of teletherapy and brachytherapy, as discussed below; these techniques are often used together. Less frequent therapeutic practice with unsealed radionuclides (radiopharmaceuticals) is considered in Chapter V. In view of the intense radiation sources used in radiotherapy and

the very nature of such treatments, there is a significant potential for accidents that would have serious consequences for the health of both patients and staff; such incidents are discussed further in Chapter VII.

A. TECHNIQUES

135. The principal treatment modality in radiotherapy is with external beams of radiation from x-ray or sealed radionuclide sources focused on the target volume (teletherapy). X-ray beam therapy machines are broadly classified into kilovoltage units (40–300 kV) and, for deep-seated tumours, megavoltage (or supervoltage) units (above 1 MV) [P34]. Kilovoltage units are further classified into contact units (40–50 kV), superficial units (50–150 kV), and orthovoltage (deep therapy) units (150–300 kV). Contact, superficial and orthovoltage machines utilize conventional x-ray tubes, whereas megavoltage therapy is based on photon beams from linear accelerators (LINACS) typically operating up to 25 MV or sealed radionuclide sources, principally ^{60}Co. Superficial treatments can also be carried out using electron beams from LINACS. In the United Kingdom, for example, approximately 15% of patients at the larger radiotherapy centres are treated with electrons, mostly using a single static field technique [A18]. Therapeutic irradiations are generally partial-body in nature, although large-field techniques are also used: total-body irradiation in conjunction with bone marrow transplantation for the treatment of leukaemias, hemi-body irradiation for the palliation of painful bone metastases, mantle irradiation in the treatment of lymphomas, and irradiation of the whole central nervous system in the treatment of medulloblastoma [S24, W22]. Radiotherapy with external beams seeks to provide an optimal distribution of dose to the target volume relative to normal tissue. This aim is pursued through careful planning and delivery of treatment. The process involves appropriate attention to radiation type, beam energy, and field size as well as the use of multifield techniques, individual blocks, multileaf collimators, wedges, bolus material, compensators, immobilization devices, simulation, port films, on-line digital imaging devices, and *in vivo* dosimetry.

136. The second important treatment modality in radiotherapy is brachytherapy, in which an encapsulated source or a group of such sources is positioned on or in the patient by surface, intracavitary, or interstitial application so as to deliver gamma or beta radiation at a distance of up to a few centimetres [D46]. Radium-226 sources, on the basis of which many brachytherapy techniques were developed, are not ideal, and the trend, particularly in developed countries, is for their replacement by a variety of artificial radionuclides [T4]. Sources may be implanted temporarily or permanently using four basic techniques of application: direct implantation into body tissues, as in conventional interstitial therapy; implantation of holders, applicators, or moulds preloaded with sources (as in intracavitary and surface therapy); positioning of empty sleeves, containers, or applicators for the manual afterloading of sources; and remote afterloading of sources into applicators by mechanical transport along a coupling to a storage safe [S25].

137. Permanent brachytherapy implants are generally used for deep-seated tumours such as cancers of the pancreas, lung, brain, pelvis, and prostate, often for palliative treatment [S25]. The most commonly used sources are ^{125}I, ^{198}Au, and ^{103}Pd, either as individual grains (seeds) or loaded in sutures. Temporary implants of ^{192}Ir (wire or pellets), ^{137}Cs (needles or pellets), and ^{60}Co (pellets) are used for superficial and easily accessible tumours. Interstitial applications are used in treatments of the breast, head and neck, cervix, vagina, rectum, and prostate. The intracavitary implant technique is routinely used in the treatment of carcinomas of the cervix, vagina, and endometrium. Intraluminal implants, using a special applicator or catheter, are used in the treatment of carcinomas of the oesophagus, bronchus, and bile ducts [S26]. Removable ophthalmic plaques are used for treating malignant melanoma of the uvea and other tumours of the eye [H19]; medium-sized and large tumours are usually treated with ^{103}Pd or ^{125}I applicators, and small tumours with beta-ray applicators incorporating ^{106}Ru or ^{90}Sr.

138. Brachytherapy is often used in combination with external beam therapy [W22]. For example, in the management of cancer of the cervix, teletherapy is used to treat the parametria and pelvic nodes, with intracavitary treatment being used principally for the primary tumour. Tumours of the tongue and breast are often given preliminary treatment by teletherapy, with brachytherapy providing a boost in the dose to the primary tumour. Various multi-centre studies are in progress to investigate the efficacy of endovascular brachytherapy treatment for the inhibition of restenosis after angioplasty [W29].

139. Conventional low-dose-rate (LDR) brachytherapy using ^{137}Cs (or ^{226}Ra) sources involves dose rates at the prescribed point or surface in the range 0.4–2.0 Gy h^{-1}, with most treatments given over a period of several days in one or possibly two fractions; higher-activity ^{137}Cs sources can provide medium dose rates (MDR) of up to 12 Gy h^{-1}. High-dose-rate (HDR) brachytherapy utilizes ^{192}Ir or ^{60}Co sources to provide even higher dose rates, generally 2–5 Gy min^{-1}, with treatment times reduced to hours or even less and perhaps using several fractions [B5, I14]. Remote afterloading is essential, from a radiological protection point of view, for HDR and MDR techniques. Other developments in radiotherapy are discussed below in Section IV.E.2 in relation to trends in the practice.

B. DOSIMETRY

140. The success of radiotherapy depends on the accurate and consistent delivery of high doses of radiation to specified volumes of the patient, while minimizing the

irradiation of healthy tissue. Detailed assessment of the dose for individual patients is critical to this aim, and techniques for dosimetry and treatment planning are well-documented; see, for example, publications from ICRU [I11, I12, I13, I14, I15, I16, I21, I33], IAEA [I8, I9, I10, I20], and others [A12, B18, B19, W24], as well as various codes of practice (see, for example, [K10, N14, N17, N43, T6]). Special treatment and dosimetry techniques are required for pregnant patients to minimize potential risks to the fetus from exposure *in utero* [A37, M74, S27]; approximately 4,000 such women required treatment for malignancy in the United States in 1995. Radiotherapy can cause permanently implanted cardiac pacemakers to malfunction, and special techniques have been recommended for the planning and administration of treatment on such patients [L21]. Quality assurance measures and dosimetry intercomparisons are widely recommended to ensure continuing performance to accepted standards [D3, D13, K3, K14, N18, N44, W14].

141. Broadly, the elements of clinical radiation oncology include assessment of the extent of the disease (staging); identification of the appropriate treatment; specification of a prescription defining the treatment volume (encompassing the tumour volume), intended tumour doses and consideration of critical normal tissues, number of fractions, dose per fraction, frequency of treatment, and overall treatment period; preparation of a treatment plan to provide optimal exposure; and delivery of treatment and follow-up. X-ray imaging, and CT in particular, is widely used throughout this process; applications include the assessment of disease, preparation of the plan, checking the location of brachytherapy sources, or, using treatment simulators, checking correct patient set-up for external beam therapy. In view of the largely empirical nature of current practice in radiotherapy, significant variations are apparent in the dose/time schedules used in the treatment of specific clinical problems [D19, D24, G20, N19, P4, U14].

142. *In vivo* dosimetry is conducted to monitor the actual dose received by the patient during treatment in order to check the accuracy of delivery and as a means of determining the dose to critical organs, such as the lens of the eye or the spinal cord [E5, M17]. Both TLD [D18, K24] and solid state [A9, B34, C15, E6, S94, V4, W36] detectors are used. *In vivo* dosimetry is particularly useful during conformal radiotherapy [L46]. Also, electron spin resonance (ESR) in dental enamel has been investigated as a potential means of retrospective dosimetry for validating doses delivered to the head and neck regions [P7]. Portal films and digital imaging devices visualizing exit fields are used to verify the positional accuracy of external beams during treatment and, increasingly, to provide quantitative dosimetric information [A8, S31, T10]. Radiochromic film is also used for quantitative planar dosimetry to map dose distributions, for example, in low- and high-dose-rate brachytherapy, stereotactic radiosurgery, and beta-ray ophthalmic plaque therapy [N42, Z7].

C. ANALYSIS OF EXPOSURES

1. Frequency of treatments

143. Differences in the resources available for radiotherapy lead to wide variations in national practice, with many smaller countries or LDCs having no treatment facilities or only a few. Annual numbers of treatments reported by different countries from 1991 to 1996 are summarized in Tables 51 and 52 for teletherapy and brachytherapy procedures, respectively. The data are presented in terms of numbers of treatments per 1,000 population by disease category, with countries grouped according to health-care level. Important qualifications regarding the derivation of some of these figures are given in the footnotes. The percentage contributions by disease category to the annual total frequencies of radiotherapy treatments are shown in Tables 53 and 54 for teletherapy and brachytherapy, respectively. Mean values of frequencies have been derived for each health-care level by averaging total numbers of procedures over total populations.

144. Patterns of practice vary significantly from country to country, even within a single health-care level. Annual frequencies of teletherapy treatments differ by a factor of over 30 within the sample of 28 countries in health-care level I (0.1–3.7 treatments per 1,000 population); disregarding countries with zero practice, similarly large variations exist in level II (0.05–3.1 treatments per 1,000 population in a sample of 19 countries) and level III (0.05–2.1 treatments per 1,000 population in a sample of 6 countries). Information was available from only one country in health-care level IV (United Republic of Tanzania: 0.05 treatments per 1,000 population). The average total frequencies for teletherapy in levels II and III are smaller by factors of 2.2 and 3.2, respectively, than the average for level I (about 1.5 treatments per 1,000 population). These averages are very much less than the corresponding average for the use of x rays in each level. Teletherapy treatments are, in general, also less common than diagnostic nuclear medicine procedures, by a factor of over 10 in the case of level I, but by nearer a factor of 2 for the lower levels. The average frequency of brachytherapy treatments in level I (0.2 treatments per 1,000 population) is less than one seventh of that for teletherapy. In levels II and III, practice in brachytherapy is lower by a factor of about 10 compared with level I.

145. Notwithstanding differences between the individual countries, some broad patterns of practice in radiotherapy are apparent from the average frequencies of use for the different health-care levels. In general, teletherapy is widely used in the treatment of breast and gynaecological tumours, although there is also significant use for treatments of the prostate and lung/thorax in countries of level I, and for treatments of the head/neck in levels II and III. Brachytherapy practice is universally dominated by treatments of gynaecological tumours. Temporal trends in the frequency of examinations are discussed in Section IV.E.

2. Exposed populations

146. The distributions reported by different countries of the age and sex of patients undergoing teletherapy and brachytherapy treatments for various diseases in 1991–1996 are presented in Tables 55 and 56, respectively. As was done for previous analyses of exposed populations, three ranges of patient age have been used, and the countries are listed by health-care level; some qualifications to the data are given in the footnotes. As might be expected since radiotherapy is primarily employed in the treatment of cancer, therapeutic exposures are largely conducted on older patients (>40 years), with the skew in ages being even more pronounced than for the populations of patients undergoing diagnostic examinations with x rays or radiopharmaceuticals. However, significant numbers of children undergo teletherapy for the treatment of leukaemia and lymphoma. Once again, countries in the lower health-care levels exhibit a shift towards the younger age ranges for most treatments, relative to level I countries, probably as a result of underlying differences in national population age structures [U3].

147. For certain teletherapy and brachytherapy procedures, there are obvious links to patient sex, for example, the treatment of breast and gynaecological tumours in females and prostate tumours in males. For other treatments, there is a general bias towards males in the populations of patients.

3. Doses from treatments

148. In the present review, the doses received by patients from radiotherapy are summarized in terms of the prescribed doses to target volumes for complete courses of treatment, as discussed in Section I.C. The typical prescribed doses reported by different countries for 1991–1996 are presented in Tables 57 and 58 for practices in teletherapy and brachytherapy, respectively. The average doses shown for each type of treatment and health-care level include weightings for the numbers of treatments in each country. Prescribed doses are typically in the range 40–60 Gy for most treatments, with somewhat lower doses being used in relation to radiotherapy for leukaemia and benign disease.

149. Some information is available concerning the doses to individual organs and tissues during radiotherapy treatments and examples can be given (see, for example, [D45, G46, H56, H57, L47, T23]). *In vivo* and phantom measurements have been performed to study inhomogeneities in dose during total body irradiation prior to bone marrow transplant [B37, B38]. A comparison of two commonly used techniques for external beam therapy of nasopharyngeal carcinoma concluded that the extended neck technique generally resulted in lower doses to most normal structures, although the flexed neck technique provided better coverage and uniformity of dose to the target volume [W27]. Measurements have been reported in relation to the distributions of dose over different body parts for patients undergoing radiotherapy treatments in Bangladesh [B44, M26]. A study of the doses to 13 specific sites in children undergoing radiotherapy for Hodgkin's disease has demonstrated wide variations between individual patients in a multicentre European cohort [S43]. During the treatment of cervical cancer with external ^{60}Co therapy in Mexico, the mean doses to the circulating blood and lymphocytes were estimated by probabilistic modeling to be about 2% and 7%, respectively, of the tumour dose [B24]. Dosimetric modeling for ophthalmic brachytherapy of the sclera with an ideal ^{90}Sr applicator has indicated a dose rate to the most radiosensitive areas of the lens of the eye ranging from 88 to 155 mGy s^{-1} [G24].

150. In teletherapy with photon beams, the doses at great distances from the target volume arise from several sources: radiation scattered in the patient; leakage and scattered radiation from the treatment head of the machine (the collimator-related radiation); and radiation scattered from the floor, walls, or ceiling [V6]. The first and third contributions depend on field size, distance, and photon energy and can be measured and applied generally. The second contribution is machine-dependent and in principle requires measurement for individual machines; collimator scatter varies according to specific design, although levels of leakage radiation are rather similar for all modern equipment, corresponding to an average value of 0.03 ± 0.01% (relative to the central axis dose maximum) in the patient plane at a distance of 50 cm from the beam axis. When the distance between the gonads and the primary beam is large (around 40 cm, for example, in the treatment of breast cancer), gonad dose is determined primarily by the leakage radiation. Specific data have also been reported in relation to the peripheral dose during therapy using a LINAC equipped with multileaf collimation [S96]. Leakage radiation might not be insignificant during high-energy electron treatments, although the associated risks to patients should be judged in the context of the therapy [M14].

151. The broad ranges of gonad doses from photon teletherapy treatments for some specific tumour sites shown in Table 59 are based on measurements in a patient population [V6]. The minimum and maximum values are determined not only by the range of tumour doses considered but also by the range of field sizes and distances encountered in clinical practice, with due account taken of the variation in distance to the gonads between men and women. For treatments in the pelvic region, gonad doses can range from tens of milligrays to several grays, depending on the exact distance from the centre of the treatment volume to the gonads.

152. In brachytherapy, where radiation sources are inserted directly into the body, the dose to peripheral organs is determined primarily by their distance from the target volume. The decrease in dose with distance from a brachytherapy point source can be described by the inverse

square law, modified by a factor to account for scatter and absorption in tissue, and experimental data have been reported to allow the estimation of dose in the range 10–60 cm from ^{60}Co, ^{137}Cs, and ^{192}Ir sources [V6].

153. The skin-sparing nature and clinical efficacy of high-energy photon beams can be compromised by electron contamination arising from the treatment head of the machine and the air volume, and comprehensive dosimetric assessment requires taking into consideration the effect of this component on the depth-dose distribution [H58, S12, Z8]. Electrons and photons with energies above 8 MeV can produce neutrons through interactions with various materials in the target, the flattening filter, and the collimation system of the LINAC, as well as in the patient [K17]. For a typical treatment of 50 Gy to the target volume using a four-field box irradiation technique with 25 MV x rays, the additional average dose over the irradiated volume from such photoneutrons is estimated to be less than 2 mGy and quite negligible in comparison with the therapeutic dose delivered by the photons [A10]. The average photoneutron dose outside the target volume would be about 0.5 mGy under the same circumstances, and for peripheral doses this component could be similar in magnitude to the contribution from photons [V6]. High-energy x-ray beams will also undergo photonuclear reactions in tissue to produce protons and alpha particles [S95], with total charged particle emissions exceeding neutron emissions above 11 MeV [A11]. However, these charged particles have a short range, so any additional dose to the patient will mostly be imparted within the treatment volume and will be insignificant.

D. ASSESSMENT OF GLOBAL PRACTICE

154. The data in Tables 51 and 52 provide robust estimates of the annual total numbers of teletherapy and brachytherapy treatments per 1,000 population within each health-care level; the frequencies of teletherapy in levels II and III may have been overestimated since some of the national data used refer to numbers of cancer patients rather than treatments, although these sources of uncertainty will be reduced when considering global practice. However, the mean values shown in Table 51 and 52 for the individual types of treatment within each health-care level have had to be averaged over different populations due to the lack of comprehensive information for all countries listed and so do not represent a self-consistent set of data. More robust estimates have therefore been derived by scaling the observed average relative frequencies for each type of treatment (Tables 53 and 54) by the mean total frequencies calculated for each health-care level. These final data for the global model of radiotherapy practice for 1991–1996 are shown in Table 60. Analyses are presented separately for both teletherapy and brachytherapy, although the limited data available for the latter practice in health-care levels III and IV have been pooled so as to provide more reliable estimates for a combined population. The estimates of world practice have been calculated using the global model of population described in Section I.D. The uncertainties inherent in the estimates of mean frequencies provided by the global model are difficult to quantify, but will be significant, particularly when extrapolations have been made on the basis of small samples of data.

155. According to the model developed, the global annual frequencies assessed for radiotherapy treatments during 1991–1996 are dominated by the national practices in health-care level I, which provide contributions of about 50% and 80% to the total numbers of teletherapy and brachytherapy treatments, respectively, in the world (Table 9). The most important uses of teletherapy are for treatments of breast, lung and gynaecological tumours, whilst practice in brachytherapy is principally concerned with the treatment of gynaecological tumours, although some differences are apparent between the mean frequencies for the different health-care levels. The global frequency assessed for brachytherapy treatments (0.07 per 1,000 population) is less than one tenth that for teletherapy treatments (0.8 per 1,000).

156. Global resources for high-energy radiation therapy using teletherapy equipment with ^{60}Co sources or higher-energy photon beams were summarized for the 1980's by WHO [H20]. This analysis suggested that in some parts of the world, such as Africa and South-East Asia, there might have been only one high-energy radiation therapy machine for 20–40 million people, and one machine might be used to treat more than 600 new patients per year. Many cancer patients had no access to radiotherapy services [B33]. The results of a more recent analysis for 1998 are presented in Table 61 [D27]. The resources for radiotherapy are still very unevenly distributed around the world, with equipment numbers per million population being much higher in North America, Australasia and Western Europe, than in Central Africa, the Indian Subcontinent and East Asia. Only 22 out of 56 countries in Africa were known with confidence to have megavoltage therapy, and these are concentrated in the southern and northern extremes of the continent [L45]. The total of 155 megavoltage units operating in Africa in 1998 represented an increase by more than a factor of 2 over the total for 1991. The population served by each megavoltage machine ranged from 0.6 to 70 million; overall, only half of the population of Africa had some access to radiation oncology services.

157. Radiation therapy equipment and services are also very unevenly distributed in the Latin American and Caribbean countries [B33]. In 1994, there were approximately 500 ^{60}Co units, 10 ^{137}Cs units, and 124 LINACS. Services tend to be concentrated in the larger countries of South America (especially Argentina, Brazil, Colombia, and Venezuela) and in Mexico. A similar pattern prevails in the countries of the English-speaking Caribbean; the most well-equipped services are found in Barbados (which also treats patients from some other countries), Jamaica, and Trinidad and Tobago.

E. TRENDS IN TELETHERAPY AND BRACHYTHERAPY

1. Frequencies of treatments

158. Temporal trends in the normalized annual frequencies of teletherapy treatments and brachytherapy treatments are summarized in Table 62. When comparing these data, it should be remembered that the averages for each time period have been made over different populations and often with small sample sizes. The present estimates of average total frequency of teletherapy treatments per 1,000 population in each health-care level are larger than the previous values for 1985–1990: 1.5 versus 1.2 in level I, 0.7 versus 0.2 in level II, and 0.5 versus 0.1 in level III, respectively. These apparent increases will be due in part to the inclusion in the present analysis of some data concerning numbers of new cancer patients in lieu of more specific treatment data. No particular trends with time are apparent from the estimated data concerning the frequencies of brachytherapy treatments. Notwithstanding these overall trends in average frequency for the different health-care levels of the global model, national frequencies for individual countries have increased in some and decreased in others between 1985–1990 and 1991–1996; some specific examples are given below. The available data concerning temporal trends in the average annual numbers of different types of treatment per 1,000 population by health-care level are summarized in Table 63.

159. In many countries, the utilization of radiotherapy has increased steadily over the last thirty years. In the United States, for example, the resources available for radiotherapy rose from 1,047 facilities (with a total of 1,377 treatment machines) in 1975 to 1,321 facilities (and 2,397 machines) in 1990 [I23]. Over this period, the annual number of new patients undergoing radiation therapy has correspondingly increased from 1.5 to 2.0 per 1,000 population. In Russia, the annual number of radiotherapy treatments increased steadily from a rate of 1.0 per 1,000 population in 1980 to 1.7 per 1,000 in 1997. Steady increases have also been reported elsewhere, such as in New Zealand and Sweden (Table 62). In other countries, rates of practice have either remained fairly static (in Australia and Japan, for example) or have apparently declined (in Romania, for example).

2. Therapeutic practices

(a) Teletherapy

160. Over the last 50 years, there have been continuing advances in engineering, the planning and delivery of treatment, and clinical radiotherapy practice, all with the aim of improving performance [B75]; some key technical developments in teletherapy are listed in Table 64. In developed countries at least, there has been growing use of high-energy linear accelerators for the effective treatment of deep-seated tumours; Figure VII illustrates the decline in the number of telecobalt units and the increase in linear accelerators in France over the last 10 years [L13]. Similar trends are broadly apparent in Table 7 for the mean numbers of the different types of radiotherapy equipment per million population in the different health-care levels. It has been suggested that the energy ranges 4–15 MV for photons and 4–20 MeV for electrons are those optimally suited to the treatment of cancer in humans [D14]. Units with ^{60}Co sources remain important for developing countries in view of the lower initial and maintenance costs and simpler dosimetry in comparison with LINACS, although replacement sources of the longer-lived radionuclide ^{152}Eu are under consideration as being potentially more efficient for such units [A5].

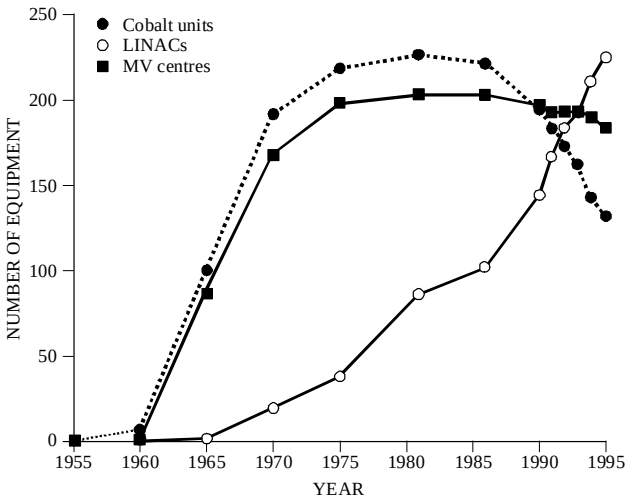

Figure VII. Radiotherapy centres (with mega-voltage equipment), telecobalt units and linear accelerators in France [L13].

161. Developments in diagnostic imaging, such as CT and MRI, have benefitted the assessment of disease and also the planning and delivery of therapy [C52, R39]. Treatment plans are calculated using sophisticated computer algorithms to provide three-dimensional dose distributions, including so-called beams-eye views, and Monte Carlo simulation techniques are being adopted [M76, S100]. Computer control of the linear accelerator has facilitated the development of new treatment techniques. Multileaf collimators can not only replace the use of individual shielding blocks in routine treatments with static fields as a tool for sparing healthy tissues, but can also allow the achievement of computer-controlled conformal radiation therapy [G23]. This type of therapy seeks to provide optimal shaping of the dose distribution in three dimensions so as to fit the target volume [D26, F3, L10, S34]; developments include tomotherapy, which uses slit beams provided by dynamic control of multileaf collimators coupled with movement of the gantry during treatment [Y7]; intensity-modulated arc therapy, which combines spatial and temporal intensity modulation [B36, K15, Y3]; and adaptive radiation therapy, in which treatment plans for individual patients are automatically re-optimized during the course of therapy on the basis of systematic

monitoring of treatment variations [Y5]. The success of such therapies is compromised by intrafraction organ motion [Y6], and synchronous gating of the radiation beam with respiration is being investigated [K8]. *In vivo* dosimetry [B20, B26, M17, S17], phantom dosimetry [D17, M15, O5] and imaging [H59, R39] are increasingly being used to verify that the machine and patient set-up are as required for the prescribed treatment and to assure the accuracy of plans. In particular, electronic portal imaging provides real-time verification of patient position and is being developed for transit dosimetry so as to allow comparison of the delivered dose distribution relative to the treatment plan [H4, H13, K58, M16, P36, S32].

162. Technical advances in the execution of radiotherapy have stimulated further research into clinical radiobiology [D20, G19, L10, S99, W23]. New methods are required to summarize and report the inhomogeneous dose distributions delivered to irradiated organs and volumes of interest [N20]. Studies in cellular and tissue biology have provided a scientific rationale for developments in hyper-fractionation and accelerated treatments to improve the therapeutic ratio in radiotherapy (normal tissue tolerance dose relative to tumoricidal dose). Several clinical trials are in progress [B21, D4, S33], and the use of hyperfractionation is likely to increase.

163. Radiotherapy is performed less often to treat benign disorders, because there is no clear biological rationale or experimental data, and also because there are concerns that such treatments might induce cancer in the exposed patients [B79, S22]. A survey conducted in 1996 detected large variations in practice throughout the world in relation to the indications and treatment schedules for radiotherapy of benign diseases [L24]. In the United States and Europe (especially Germany), low-dose orthovoltage therapy is currently well-accepted practice for the treatment of several selected benign conditions such as the prevention of heterotopic ossification after hip replacement, the stabilization and improvement of patients with Graves disease, keloid prevention, and achillodynia syndrome. Radiotherapy is also employed in the treatment of benign tumours and, using radiosurgery, vascular malformation. It has been argued that radiation therapy should also be considered as the primary modality for treating refractory pain in plantar heel spur [S22]. It has also been suggested, on the basis of experiments with animal coronary models and anecdotal reports of treatment to human femoral arteries, that acute localized delivery of 15–20 Gy to the walls of blood vessels can reduce the rate of restenosis following angioplasty [A4, W29]. Although external beam therapy has been proposed as one possible approach, most interest has centred on the development of endovascular brachytherapy techniques [F23, N45], and these are reviewed briefly in the next Section.

(b) Brachytherapy

164. Intracavitary brachytherapy for gynaecological cancer using radium (^{226}Ra) was one of the first radiotherapeutic techniques to be developed. This radionuclide has now largely been replaced in developed countries by ^{137}Cs, although radium sources are still utilized for economic reasons in some areas of the developing world and eastern Europe [B5]. The remote afterloading technique is becoming standard practice in Europe for the treatment of carcinoma of the cervix and is increasingly being used for interstitial implants in relation to the bronchus, breast, and prostate [S25]. HDR brachytherapy offers advantages over the LDR technique in terms, for example, of improved geometrical stability during the shorter treatment times and reduced staff exposures; however, the relative loss of therapeutic ratio requires modified treatment schedules to avoid late normal tissue damage and so allow cost-effective therapy [J1, J17, T5]. Pulsed dose-rate (PDR) brachytherapy has been developed in the hope of combining the advantages of the two techniques, while avoiding their disadvantages [B25, M18]. In essence, a continuous LDR interstitial treatment lasting several days is replaced with a series of short HDR irradiations, each about 10 minutes long, for example, and given on a hourly basis, so as to deliver the same average dose. Each pulse involves the stepping of a single high-activity source through all catheters of an implant, with computer-controlled dwell times in each position to reflect the required dose distribution.

165. Endovascular brachytherapy treatments to inhibit restenosis after angioplasty have been performed experimentally using catheters for the temporary implantation of radioactive seeds and wires (^{192}Ir and ^{90}Sr/^{90}Y) and also for the permanent implantation of radioactive stents (^{32}P) [C16, J7, J18, T11, V7]. The proton-beam activation of nickel-titanium alloy stents to produce ^{48}V could provide a unique mixed gamma/beta source to allow an improved dose distribution for this application [L22]. One other possible irradiation technique in the course of an angioplasty procedure would involve filling the dilatation catheter balloon with a high-activity beta-emitter such as ^{90}Y [A4] or ^{188}Re [K60]. Preliminary human trials of such endovascular treatments are in progress at several centres around the world [P45, W29].

(c) Other modalities

166. The continuing obstacle to definitive radiotherapy is the difficulty of delivering lethal doses to tumours while minimizing the doses to adjacent critical organs. Various special techniques have been developed to overcome this limitation, although such modalities are less common practice than the techniques discussed above. Intraoperative radiation therapy (IORT) involves surgery to expose the tumour or tumour bed for subsequent irradiation, usually with a beam of electrons in the energy range 6–17 MeV, while normal organs are shifted from the field [D15]. The entire dose is delivered as a single fraction in complex configuration, which makes dose control and measurement particularly critical [B22]. A total of approximately 3,000 patients are estimated to have been treated

with IORT worldwide by 1989, mostly in Japan and the United States. A recent development for the treatment of primary bone sarcomas is extracorporeal radiotherapy, in which the afflicted bone is temporarily excised surgically so that it can undergo high-level irradiation in isolation before immediate re-implanting [W15]. Studies have also been made of the potential enhancement of dose to the target volume using the technique of photon activation, in which increased photoelectric absorption is achieved by loading the tissue with an appropriate element prior to irradiation. Modeling has been reported for therapeutic applications of iodine contrast agents in association with a CT scanner modified for rotation x-ray therapy [M75, S35] and for a silver metalloporphyrin for use in interstitial brachytherapy with ^{125}I seeds [Y8].

167. Stereotactic radiosurgery (SRS) refers to the use of thin, well-defined beams of ionizing radiation for the precise destruction of a well-defined intracranial target volume at the focus of a stereotactic guiding device, without significant damage to adjacent (healthy) tissues. Since introduction of the technique in 1951, clinical studies have been undertaken with high-energy photons from linear accelerators [F12] and ^{60}Co sources, with protons, and with heavy particles. The Leksell Gamma Knife (LGK) contains 201 fixed ^{60}Co sources arranged in a concave half-spherical surface and is the most common equipment for conducting SRS [E7, G25]. There were 90 such devices in use worldwide in 1997, of which 32 were in the United States. Data from the present UNSCEAR Survey of Medical Radiation Usage and Exposures indicate a total of 20 gamma knives in Japan and 36 in China; some limited additional information is given in Table 5. An analysis published in 1996 indicated that nearly 30,000 patients had been treated with the LGK since 1968. Doses to extracranial sites during LGK treatments have been reported to be relatively low, with the eyes receiving about 0.7% of the maximum target dose and doses to other sites decreasing exponentially with increasing distance from the isocentre of the LGK unit [N22]. SRS treatments for small lesions (up to approximately 4 cm in diameter) are delivered in a single session, although fractionated regimes are under development for larger tumours. Isocentric ^{60}Co units could represent viable alternatives to LINACS as radiation sources for conducting SRS [P35]. Diamond detectors are expected to allow more accurate dosimetry for SRS in comparison with traditional methods involving diodes, films, ionization chambers, or TLDs [E8, H14, V5]. A frameless robotic radiosurgery system has been developed in which real-time x-ray imaging of the patient locates and tracks the treatment site during exposure and so provides automatic targeting of a 6 MV photon beam [M20]. Trials are also in progress with a novel miniature x-ray source for stereotactic interstitial radiosurgery, in which a needle-like probe is used to deliver relatively low-energy photons directly into a lesion. The intensity and peak energy are adjustable for optimal tumour dose while minimizing damage to surrounding healthy tissue [B23, B74, D10, Y17].

168. New and improved radiation sources for radiotherapy are also being developed. Pencil beams of high-energy photons can theoretically be produced by the Compton backscattering process during collisions between low-energy photons and high-energy electrons stored in magnetic ring structures [W25]. Such photon beams could be used for the production of radionuclides, the generation of positrons and neutrons, conventional high-energy teletherapy, and, for example, functional radiosurgery through the intact skull of small deep-lying targets within the brain [G9]. Whereas most radionuclides for medical use are produced in a nuclear reactor or cyclotron, it is possible that small amounts of radionuclides could be produced by the mechanism of direct electron activation using a medical linear accelerator [W26].

169. There are potential advantages in conducting radiotherapy with high-energy, heavy charged-particles such as protons and heavy ions. Such charged-particle beams can provide superior localization of dose at depth within target volumes. Furthermore, heavy ions with high linear energy transfer (LET) components can damage cells in locally advanced radioresistant tumours more effectively than low-LET radiations such as photons or protons [B72]. Proton beams have been used therapeutically since 1955 and represent the treatment of choice for ocular melanoma [B73, I33]. Protons have also been used to treat deep-seated tumours. As of 1996, there had been approximately 17,000 patient treatments worldwide, with 17 facilities actively engaged in proton therapy and another 14 in various stages of planning [M12, S13, S108]. Secondary neutrons and photons make small contributions to the patient dose during proton therapy [A17]. Over 2,500 patients have been treated worldwide with heavy ions (helium or carbon) on the basis of their favourable physical and radiobiological characteristics, such as high relative biological effectiveness, small oxygen effect and small cell-cycle dependence [K9]. In 1996, only two facilities were operational in the world: HIMAC, Japan and GSI, Germany [J16]. About 600 patients with various types of tumour located in various organs have already been treated with a carbon beam at the HIMAC facility since 1994 [K57]. In addition, about 1,100 patients were treated with negative pi mesons between 1974 and 1994, although with no active facilities in 1996, this is not a significant modality [J16].

170. Fast neutron radiation therapy was first used as a cancer treatment tool in 1938 in the United States, but it was not successful, because the radiobiology was not fully understood [G10]. Later studies in the United Kingdom in the 1960s with appropriate fractionation paved the way for clinical trials at various centres around the world. In particular, a 20–year multiphase project was begun in the United States in 1971; the project has involved 10 separate neutron facilities and several thousand patients to establish the efficacy of neutron therapy. Clinical experience over two decades with neutron therapy for pancreatic cancer has demonstrated high complication rates and overall survival rates that are no better than those achieved with conven-

tional radiotherapy alone [D21]. Neutron brachytherapy using ^{252}Cf sources is being carried out at one medical centre in the United States [M24].

171. There is also renewed interest in the bimodal treatment technique of boron neutron capture therapy (BNCT), in which boron (^{10}B) is selectively concentrated in malignant tissue for subsequent activation (transmutation to ^{11}B with the emission of alpha particles and ^{7}Li ions) when irradiated with thermal neutrons [B35, C51, D16, G21]. Early clinical trials in the United States in the 1950s were followed by large studies in Japan and proposals for further work in the United States and Europe as a result of the development of second-generation boron compounds and the availability of reactor-based epithermal neutron beams [A6, G45, R8]. Particle accelerators can also be used to provide beams of neutrons for BNCT, and this approach offers the potential for application in hospitals [G22]. By its nature, BNCT will be most suited to the treatment of localized tumours such as high-grade gliomas that cannot be treated effectively by other types of therapy. The technique is also under investigation for synovial ablation in the treatment of rheumatoid arthritis [Y16].

172. Cancer is likely to remain an increasingly important disease in populations with increasing lifespans, and this will probably cause radiotherapy practice to grow in most countries. WHO estimates that, worldwide, by the year 2015 the annual number of new cancer cases will have risen from 9 million in 1995 to about 15 million, with about two thirds of these occurring in developing countries [W12]. If one half of these are treated with radiation, at least 10,000 external beam therapy machines will be required at that time in developing countries, in addition to a large number of brachytherapy units.

173. Radiotherapy involves the delivery of high doses to patients and accordingly there is an attendant potential for accidents with serious consequences for the health of patients (arising from over- or under-exposure relative to prescription) and also staff; this topic is discussed further in Chapter VII. Quality assurance programmes help ensure high and consistent standards of practice so as to minimize the risks of such accidents. Effective programmes comprehensively address all aspects of radiotherapy, including *inter alia* the evaluation of patients during and after treatment; the education and training of physicians, technologists and physicists; the commissioning, calibration and maintenance of equipment; independent audits for dosimetry and treatment planning; and protocols for treatment procedures and the supervision of delivery [D3, D13, K3, W14].

F. SUMMARY

174. Radiotherapy involves the delivery to patients of high absorbed doses to target volumes for the treatment of malignant or benign conditions. Resources for radiation therapy are distributed unevenly around the world (Tables 61, 6 and 9), with there being significant variations in radiotherapy practice both between and often within individual countries (Tables 51 and 52); many cancer patients have little or no access to radiotherapy services. Global annual numbers of complete treatments by the two main modalities of teletherapy and brachytherapy have been estimated from the scarce national survey data available using a global model, although the uncertainties in this approach are likely to be significant; the results of this analysis are summarized in Table 65. The world annual total number of treatments for 1991–1996 is estimated to be about 5.1 million, with over 90% arising from teletherapy. The corresponding average frequency of 0.9 treatments per 1,000 world population is similar to the level quoted for 1985–1990 [U3] on the basis of an estimated total number of 4.9 million treatments. The present global total of treatments is distributed amongst the different health-care levels of the model as follows: 51% in countries of level I (at a mean rate of 1.7 per 1,000 population), 43% in countries of level II (0.7 per 1,000 population), 6% in countries of level III (0.5 per 1,000 population) and 1% in countries of health-care level IV (0.07 per 1,000 population). Radiation treatments by teletherapy and brachytherapy are very much less common than diagnostic medical and dental examinations with x rays (annual global totals of 1,910 million and 520 million examinations, respectively).

V. THERAPEUTIC ADMINISTRATIONS OF RADIOPHARMACEUTICALS

175. Unsealed radionuclides (radiopharmaceuticals) have also been used as therapeutic agents for over 60 years by direct administration to the patient. Such treatments play a small but important role in the management of patients with cancer, generally from a palliative point of view, and with other conditions such as thyroid disease and arthritis [B76]. For several benign disorders, radionuclide therapy provides an alternative to surgical or medical treatment; for the treatment of malignant disease, this modality combines the advantage of being selective (like teletherapy or brachytherapy) with that of being systemic (like chemotherapy) [H60].

A. TECHNIQUES

176. Radiotherapy with unsealed radionuclides offers the potential advantage of allowing the biological targeting of the radiation absorbed dose to particular tissues or regions

of the body. In clinical practice, biologically targeted radiotherapy for cancer requires a molecule that has a relative specificity for tumour tissue (delivery to the target tissue) coupled to a radionuclide with appropriate physical characteristics (imparting the dose) [G6]. When administered systemically (by ingestion or injection) or regionally (by infusion) to a patient, this combination in principle allows for the selective irradiation of target tumour cells, even in widespread disease, with relative sparing of normal tissues. The choice of an appropriate radionuclide is governed by the quality and path length of the radiation (relative to target size), physical half-life, gamma yield, chemistry, cost, and availability. Clinical practice at present is centred on radionuclides that emit medium-energy beta radiation with a range of a few millimeters in tissue.

177. The most common examples of such biologically targeted therapies involve simple ions and small molecules that follow physiological pathways, such as ^{131}I sodium iodide for the treatment of thyroid carcinoma, ^{32}P sodium orthophosphate for the treatment of polycythemia rubra vera, ^{89}Sr strontium chloride for the management of painful bone metastases, and ^{131}I meta-iodobenzylguanidine (mIBG) for the treatment of neuroblastoma [O21]. Efficient biological targeting is also possible through the use of tumour-specific monoclonal antibodies (MAbs) for delivery of appropriate radionuclides such as ^{186}Re and ^{188}Re [G6, R40]. Such techniques of radioimmunotherapy are not yet common in routine practice, although it is likely that these new therapeutic approaches will become increasingly important [B76]. Some current clinical applications of radionuclide therapy in cancer are summarized in Table 66 [Z3]; only the first four examples can be considered as established treatments. Clinical data on cancer therapy using a range of bone-seeking radionuclides has been reviewed by Lewington [L8].

178. Radionuclide therapy is important for the treatment of both malignant and benign diseases. Most of this type of cancer therapy is palliative in nature, although the treatment of thyroid carcinomas with radioiodine, which represents the earliest and most established form of therapy with unsealed radionuclides, is reliably curative [G6]. For treatment to be effective, activities of ^{131}I in the range 3–10 GBq are given to ablate the normal thyroid gland and to treat metastases [N5]. These doses may be repeated at intervals of 4–6 months until there is no clinical evidence of residual functioning thyroid tissue or metastases [G7]. Iodine-131 is also commonly used in the treatment of hyperthyroidism, although activities are generally 100–1,000 MBq, depending on the size of the gland and its ability to take up the sodium iodide [N5]. In Germany, for example, such treatments of benign thyroid disease accounted for the majority (70%) of all radionuclide therapy in 1991, with the use of ^{131}I for thyroid malignancies accounting for 22% of the total [B32].

179. Radionuclide therapy is also carried out by the direct introduction of a radiopharmaceutical into a body cavity [G7]. Colloidal yttrium silicate labelled with ^{90}Y is used for the intrapleural, intraperitoneal, and occasionally intrapericardial therapy of malignant effusions and intracavitary therapy for carcinomas of the bladder, intracystic treatment of craniopharyngioma, and intra-articular treatment of arthritic conditions of various joints (radiation synovectomies). Intracavitary injections of colloidal suspension of ^{198}Au are used for the treatment of malignant pleural effusions and malignant ascites in the abdomen. Intra-arterial administrations of microspheres labelled with ^{90}Y or ^{166}Ho are also in limited clinical use for the treatment of liver tumours [Z4].

B. DOSIMETRY

180. Radionuclide therapy requires detailed patient dosimetry in order to balance the therapeutic aim of treatment against the protection of normal tissues. A wide range of complex techniques is used, including macroscopic approaches to dosimetry on the scale of organs. These methods are similar to those used for diagnostic examinations with unsealed radionuclides [I35] and are based on information about uptake and retention in target and other tissues derived from quantitative imaging [B16, F1, F2, O2]. Microdosimetric techniques at the cellular and subcellular levels are under development for radioimmunotherapy in order to model heterogeneities in dose distributions [B15, O22] and so evaluate and improve the efficacy of such treatments [D11, N10]. Pre-therapy imaging of patients is used to plan individual treatments, whereas imaging during therapy allows confirmation or correction of the dosimetry [E2]. Studies have also been undertaken into biological dosimetry [M81], cancer death [M82] and fetal thyroid doses [P43] following ^{131}I therapy for thyrotoxicosis. Recommendations are available concerning standard administered activities for the different types of treatment (see, for example, [A38, L48]).

181. For the purposes of this review, the practice in radionuclide therapy is summarized in terms of the broad frequency of procedures with radiopharmaceuticals and the typical levels of administered activities, for the reasons already discussed in Section I.C.

C. ANALYSIS OF EXPOSURES

1. Frequency of treatments

182. Annual numbers of therapeutic administrations of radiopharmaceuticals reported by different countries for 1991–1996 are summarized in Table 67 by category of disease. Data are presented in terms of administrations per 1,000 population, with some analysis by radionuclide and with countries grouped according to health-care level. Some important qualifications to the data are given in the footnotes. The percentage contributions by disease category to the annual total frequencies of treatments are shown in Table 68. Mean values have been derived for each health-care level by dividing the total number of procedures by the total population.

183. Patterns of practice vary significantly from country to country, with some not conducting these types of treatment at all. Annual total frequencies range from 0.01 to 0.5 treatments per 1,000 population in the sample of 33 countries of health-care level I. The average total frequencies for levels II, III, and IV are smaller by factors of 5, 8, and 400, respectively, than the average for level I, about 0.2 examinations per 1,000 population. Relative to average diagnostic practice with radiopharmaceuticals in each level, frequencies of therapeutic administrations are typically lower by factors of between 13 (in the case of level III) and 110 (level I). In turn, radionuclide therapy is less common than teletherapy, with ratios of average frequencies ranging from about 9 (for level I) to 125 (level IV), although it is broadly similar in frequency to practice in brachytherapy.

184. In all countries, practice is dominated by ^{131}I therapy for hyperthyroidism, with other conditions, particularly thyroid malignancy, also being treated in the upper health-care levels (I–II). Temporal trends in the frequency of examinations are discussed in Section V.C.

2. Exposed populations

185. The distributions by age and sex of patients undergoing various types of therapy with radiopharmaecuticals in 1991–1996 are presented in Table 69 for different countries, grouped by health-care level; some of these data are derived from surveys of limited scope, as indicated in the footnotes. There are considerable variations in the national distributions reported for the various types of treatment, although the data often relate to quite small numbers of patients. In general, few treatments are carried out on children. However, since practice is dominated by treatments of the thyroid, the populations of patients receiving radionuclide therapy are younger than those undergoing most other types of radiotherapy (teletherapy and brachytherapy). Averages for the four health-care levels once again suggest in general a downward shift in age for patients in countries classified in the lower levels, relative to the distribution for level I. In line with underlying patterns of disease, the majority of thyroid treatments are conducted on female patients.

3. Doses from treatments

186. The doses from treatments with radiopharmaceuticals are presently characterized in terms of the activities of radionuclide administered to the patient (Section I.C). The typical activities per treatment reported by different countries for practice during 1991–1996 are presented in Table 70. The average activities shown for each type of radionuclide treatment and health-care level include weightings for the numbers of such treatments in each country. In general, the activities of ^{131}I administered for the treatment of thyroid malignancy are about ten times higher than those used for therapy of hyperthyroidism.

D. ASSESSMENT OF GLOBAL PRACTICE

187. The estimated annual numbers of patients undergoing common types of radionuclide therapy in the world are summarized in Table 71. This analysis is based on the global model of population described in Section I.D and the average relative frequencies observed for each type of treatment (Table 68) in combination with the mean total frequencies calculated for each health-care level (Table 67). The uncertainties in this approach are difficult to quantify, but will be significant, particularly when extrapolations have been made on the basis of small samples of data.

188. The global annual frequency assessed for therapy with radiopharmaceuticals during 1991–1996 is dominated by the national practices in health-care level I, which provide a contribution of about 70% to the global total number of such treatments (Table 9). Nearly 90% of global practice is concerned with the thyroid, with about two thirds of all treatments being for hyperthyroidism, and about one quarter for thyroid cancer.

E. TRENDS IN THERAPY WITH RADIOPHARMACEUTICALS

189. The role of therapeutic nuclear medicine is expanding with the development of more pharmaceuticals, the emergence of new indications for treatment and improvements in results [I34, S101]. A survey in Europe suggested that nuclear medicine was underutilized as a therapeutic modality and numbers of such treatments were likely to undergo a rapid increase, particularly for oncological indications requiring high-dose radionuclide treatments with isolation of the patient [E15, H60]. Specific trends in practice are discussed further in the two sections following.

1. Frequencies of treatment

190. Temporal trends in the normalized annual frequencies of radiopharmaceutical treatments are summarized in Table 72. When comparing these data, it should be remembered that the averages for each time period have been made over different populations and often with small sample sizes. In general, the trend from data reported by individual countries is for an increase in their national frequency of radionuclide treatments per 1,000 population between 1985–1990 and 1991–1996. The average frequencies estimated for health-care levels I and II have also increased over this period: from 0.10 to 0.17 per 1,000 in level I, and from 0.021 to 0.036 per 1,000 in level II. No particular trend with time is apparent for the practice in health-care level III. The estimated total annual number of treatments in the world has risen from 0.21 million for 1985–1990 to 0.38 million for 1991–1996 (Table 9). The available data concerning temporal trends in the average annual numbers of different types of treatment per 1,000 population by health-care level are summarized in Table 73.

191. Some examples can be given of the trends reported by particular countries. Surveys in the United Kingdom for 1993 [E11] and 1995 [C27] have confirmed both an overall increasing use of radionuclide therapy and also a widening spectrum of the therapies being undertaken; annual numbers of treatments rose from 13,000 to 14,500, and the annual cumulative administered activity of ^{131}I, the most commonly used radionuclide, increased by 100%. In Denmark, the total number of treatments increased from 1,819 in 1993 to 2,337 in 1995. In New Zealand, the annual frequency of therapeutic administrations per 1,000 population rose from 0.09 in 1960 to a peak level of 0.18 in 1983, before falling slightly to 0.16 in 1993 [L28]. Recent levels of practice have also been fairly static in Finland, where the total numbers of treatments were 2,150 in 1994 and 2,240 in 1997 [K59]. In contrast, the annual frequency of radionuclide treatments in Russia has fallen from 0.02 per 1,000 population in 1980 to 0.01 per 1,000 in 1997.

192. On a national scale, therapeutic administrations of radionuclides are reported to account for only small fractions of the annual totals of all nuclear medicine procedures carried out: approximately 1% of practice in Australia in 1991 [C7], 2% of practices in the United States in 1991 [N13] and in New Zealand in 1993 [L28], 3% of practice in the United Kingdom in 1990 [E1], and 4% of practice in Finland in 1997 [K59].

2. Therapeutic practices

193. Targeted radionuclide therapy is becoming an increasingly popular treatment modality for cancer as an alternative or as an adjunct to external beam radiotherapy or chemotherapy [O2]. However, the full potential of such techniques will only be realized with the introduction of new radionuclides whose radiations have physical properties to match tumour size and, in particular, with the development of target-specific carrier molecules such as monoclonal antibodies [B77]. The most attractive candidates for radioimmunotherapy (RIT) are radionuclides with medium energy beta emission and a half-life of several days, such as ^{47}Sc, ^{67}Cu, ^{153}Sm, ^{188}Re and ^{199}Au [M78]; however, it has been suggested [H61] that longer-lived radionuclides such as ^{114m}In and ^{91}Y could prove more effective for RIT than the shorter-lived ^{90}Y currently in use [S102]. More effective therapy should be possible using a cocktail of radioisotopes with differing beta particle energies and ranges so as to optimize energy deposition [Z3]. Also, work is in progress on DNA-targeting molecules in combination with Auger-emitting radionuclides (such as ^{125}I, ^{193m}Pt, or ^{195m}Pt) [O1] and with alpha-emitters (such as ^{211}At, ^{212}Bi, ^{213}Bi, ^{233}Ra and ^{255}Fm) [M79, M80, V2] to provide enhanced specificity of tumour-cell cytotoxicity. Another concept under consideration is that of the *in vivo* generator, in which a parent radionuclide (such as ^{166}Dy) is administered to the patient and attached to the target molecule, with subsequent decay *in situ* to the daughter radionuclide (^{166}Ho) as a source of continuing irradiation [K61]. In the longer term, it has been suggested that ^{124}I has the potential to become a universal radionuclide in nuclear oncology, with applications for both imaging and therapy [W60].

194. In addition to the treatment of cancer, there is also continuing development and growth in therapeutic applications of radiopharmaceuticals for the palliation of bone pain [K62] (using ^{89}Sr, ^{153}Sm, ^{186}Re, ^{117m}Sn and ^{177}Lu [A38, A39]) and radiation synovectomy for the treatment of rheumatoid arthritis (using ^{90}Y, ^{198}Au, ^{169}Er, ^{153}Sm, ^{188}Re, ^{186}Re and ^{166}Ho [K63, O20, P37, W61]).

195. Computer simulations have suggested that some radionuclide therapies could be made much more effective by the use of magnetic fields to constrain the paths of beta particles and so increase the absorbed dose delivered to small tumours [R3] or to enhance the protection of bone marrow in therapeutic uses of bone-seeking radionuclides [R6]. The development of measurement methods that provide estimates of absorbed dose in bone using techniques of electron paramagnetic resonance (EPR) could lead to improvements in the dosimetry of systemic radiotherapy for osseous masses [B27].

F. SUMMARY

196. Radiopharmaceuticals are administered systemically or regionally to patients in order to deliver therapeutic radiation absorbed doses to particular target tissues, in particular the thyroid, for the treatment of benign disease and cancer. The utilization of such therapy varies significantly between countries (Table 67). Global annual numbers of radiopharmaceutical treatments have been broadly estimated from the limited national survey data available using a global model and the results are summarized in Table 74; the uncertainties in these data are likely to be significant. The world annual total number of treatments for 1991–1996 is estimated to be about 0.4 million, corresponding to an average frequency of 0.065 treatments per 1,000 world population; previous estimates of these quantities for 1985–1990 were 0.2 million and 0.04 per 1,000 population, respectively. The present global total of treatments is distributed amongst the different health-care levels of the model as follows: 68% in countries of level I (at a mean rate of 0.2 per 1,000 population), 29% in countries of level II (0.04 per 1,000 population), 3% in countries of level III (0.02 per 1,000 population) and <0.1% in countries of health-care level IV (0.0004 per 1,000 population). In comparison with the practices assessed for the other modes of radiotherapy, radionuclide therapy is much less common than teletherapy (annual global total of 4.7 million treatments), but similar in frequency to brachytherapy (total of 0.4 million).

VI. EXPOSURES OF VOLUNTEERS IN MEDICAL RESEARCH

197. The vast majority of medical exposures are conducted on individual patients or selected subgroups of the population in the routine management of health. There will also be some use of medical radiations in medical research programmes, which will involve the exposure of patients in experimental trials of diagnosis or treatment, or of healthy volunteers, for example, in the development and clinical testing of new pharmaceuticals [I22, W28]. No systematic information on such exposures of volunteers is readily available, although some examples can be given from particular countries.

198. An analysis of the research studies involving administrations of radiopharmaceuticals to volunteers conducted in Germany during 1997 and 1998 is presented in Table 75 [B78]; the majority of these studies involved PET imaging. The calculated doses exceeded 10 mSv for 70% of the volunteers in 1997 and 57% in 1998; in general, the doses to volunteers who were patients were higher than those who were healthy persons. In the United States, an analysis for the period 1996–1998 of the effective doses to 2,709 volunteers receiving administrations of radiopharmaceuticals in the course of research studies at a large hospital yielded a collective dose of 24.5 man Sv (17% of this being to healthy volunteers, 83% to diseased volunteers) [V25]; the distribution of individual effective doses was as follows: 12% of these volunteers received <0.1 mSv, 72% 0.1–10 mSv and 16% >10 mSv. In general, only small fractions of whole populations are likely to be exposed to medical radiations as volunteers in medical research programmes. For example, the number of volunteers reported to have received administrations of radionuclides in the course of medical or clinical research in the Federal Republic of Germany in 1988 represented less than 0.1% of the annual total number of routine diagnostic nuclear medicine procedures performed on patients [U3].

VII. ACCIDENTAL EXPOSURES OF PATIENTS

199. In the context of this review, an accident is any unintended event, including an operating mistake, equipment failure, or other mishap, that causes an exposure to a patient that is significantly different from an exposure received in normal practice. Such accidents can occur during diagnostic examinations utilizing x rays and administrations of radionuclides, as well as during radiotherapy. There are no universally accepted definitions of the deviations in dose inherent in "accidents", although some examples can be given from the practices in particular countries. In the United States, for example, the misadministration of radioactive material in medicine is defined by the regulatory authority as the administering of: a radiopharmaceutical or radiation from a sealed source other than the one intended; a radiopharmaceutical or radiation to the wrong patient; a radiopharmaceutical or radiation by a route of administration other than that intended by the prescribing physician; a diagnostic dosage of a radiopharmaceutical differing from the prescribed dosage by more than 50%; a therapy dosage of a radiopharmaceutical differing from the prescribed dosage by more than 10%; or a therapy radiation dose from a sealed source such that errors in the source calibration, time of exposure, and treatment geometry result in a calculated total treatment dose differing from the final prescribed total treatment dose by more than 10% [N46]. Guidelines from the United Kingdom are summarized in Table 76 in relation to the formal notification of incidents involving radiation equipment used for medical exposure [H62].

200. Radiotherapy, by its very nature, has the greatest potential for accidents with serious consequences, because the patients are deliberately exposed to intense sources of radiation. From the standpoint of the health care of a radiotherapy patient, the delivery of a dose that is too small could be just as important as the delivery of one that is too large. In general, accidents are relatively infrequent as a result of the radiation protection and quality assurance measures that are applied. However, accidental exposures continue to occur, owing to scientific, technical, and managerial failures. An analysis of two serious radiotherapy accidents in the United Kingdom argued that they might well have been avoided if a formal quality system had been adopted [M13]. A study of accidental exposures to patients in Germany yielded similar conclusions [S103].

201. In the absence of more systematic information, it is difficult from isolated reports of particular incidents (see for example [I25]) and only a limited number of broader reviews to assess with confidence the extent of accidental exposures on a global scale. However, some sources of data and examples of the different types of accident can be given. Further useful information is expected to be provided by databases on incidents involving medical radiations that are under development [H2, O4, T7]. In particular, IAEA has conducted a review of 90 accidents in radiotherapy (including teletherapy, brachytherapy, and some therapy with unsealed radionuclides) that were reported to regulatory authorities and professional associations or published in scientific journals [I40, O4]. An analysis of the initiating events and contributing factors for these accidents will allow the development of lessons to be learned and measures for prevention. The most important causes identified by IAEA, often found in combination, were the following: deficiencies in education and training;

lack of procedures and protocols for essential tasks (such as commissioning, calibration, and treatment delivery); deficient communication and information transfer; absence of defence-in-depth; and deficiencies in design, manufacturing, testing, and maintenance of equipment. A detailed study has also been conducted on the causes and impact of human error in remote afterloading brachytherapy [N21].

202. Many countries have systems for the central reporting of incidents involving medical radiations. Some of these programmes include minor occurrences not of direct relevance to the present review of accidental exposures of patients. In the United States, for example, health professionals and consumers voluntarily submit reports on all types of safety hazard encountered in radiation therapy devices to the Food and Drug Administration under the MedWatch programme. Summaries are published by the Center for Devices and Radiological Health every six months as a means of improving the quality of equipment. Formal reporting of adverse incidents in the United States is required for some diagnostic and therapeutic practice involving radionuclides. Such instances of errors and unintended events reported to the Nuclear Regulatory Commission have been used to derive some estimates of national rates of misadministration, expressed as percentages of the total number of administrations in 1992: these amounted to about 0.0002% for diagnostic nuclear medicine administrations and 0.004% for therapeutic administrations (fractions) using teletherapy and brachytherapy [I23]. However, these estimates should be regarded as very approximate.

203. In the United Kingdom, 54 instances of unnecessary or excessive medical exposures to radiation (excluding overexposures due to faulty radiation equipment) were investigated by the regulatory inspectorate between 1988 and 1994 [W18]. Since the reporting of such incidents is not mandatory, this figure is likely to be an underestimate of the true rate. Analysis by discipline reveals 39% involved diagnostic radiology, 37% radiotherapy, 20% nuclear medicine, and 4% dental radiology. Reports were most frequent in radiotherapy (involving one in three of all such departments nationally), followed by nuclear medicine (1 in 25 departments); reports were least frequent in diagnostic radiology (1 in 100 departments). About one half of the incidents involved only one patient and in general "one-off" errors. Between 1982 and 1994 in the United Kingdom, there were 47 incidents in dental radiology conducted by general dental practitioners in which ionizing radiation played a part, although only 6 of these involved possible excessive exposure [L18].

204. Some examples can also be given of audits of practice undertaken in radiotherapy departments. The detailed analysis of incident reports at one radiotherapy department in the United Kingdom indicated that problems of a technical nature affected, on average, the delivery of treatment for 4 in every 1,000 patients, although none of these incidents was regarded as being of clinical significance [W19]. Elsewhere, independent checks on dosimetry at two other departments showed serious errors in delivered doses (a deviation of more than 5% from the prescribed dose for a single field) occurring at rates of up to 11 per 1,000 [C17] and 50 per 1,000 patients [A13] in the two departments, with appropriate corrective actions having been taken where necessary.

205. Overall, it is not possible to make any worthwhile quantitative estimates of the extent worldwide of accidental exposures with medical radiations, although it can be concluded that the numbers of patients involved will generally be small in comparison with normal practice.

CONCLUSIONS

206. The use of ionizing radiation for medical diagnosis and therapy is widespread throughout the world, although there are significant country-to-country variations in national resources for and practice in medical radiology (Tables 4, 6, 8 and 9). In general, medical exposures are confined to an anatomical region of interest and dispensed for specific clinical purposes so as to be of direct benefit to the examined or treated individuals. Diagnostic exposures are characterized by relatively low doses to individual patients (effective doses are typically in the range 0.1–10 mSv) that in principle are just sufficient to provide the required clinical information, although the resulting collective doses to populations are significant. In contrast, therapeutic exposures involve very much higher doses precisely delivered to target volumes (prescribed doses typically in the range 20–60 Gy) to eradicate disease, principally cancer, or to alleviate symptoms. Relatively small numbers of diagnostic or therapeutic exposures are conducted on volunteers in controlled studies for the purposes of research.

207. Medical radiology involves a broad range of well-established techniques, and practice continues to evolve with new developments in technology. Examinations that use x rays are the most common source of medical exposure, while diagnostic nuclear medicine is conducted by administering radiopharmaceuticals to patients. Radiotherapy is mostly carried out using external beams of radiation (teletherapy), although some patients receive direct applications of sealed radionuclide sources (brachytherapy) or therapeutic administrations of radiopharmaceuticals. In general, practice in medical radiology is conducted systematically and accidents are relatively infrequent.

208. Information on medical radiation usage and the resulting exposures in different countries has been obtained by means of a widely distributed questionnaire, the UNSCEAR Survey of Medical Radiation Usage and Exposures, together with results from published studies. Assessments of practice for the entire world have once again been made on the basis of a global model in which countries are stratified into four levels of health care determined by the number of physicians per unit population; level I (at least 1 physician per 1,000 population), level II (1 physician per 1,000–3,000 population), level III (1 physician per 3,000–10,000 population), and level IV (1 physician for more than 10,000 population). The available data within each level have been averaged to provide representative frequencies or exposures that allow extrapolation to total populations.

209. The present estimates of global practice from the medical uses of radiation are summarized in Table 77, in terms of the numbers of procedures and, for diagnostic examinations, collective doses and per caput doses. These exposures are distributed unevenly amongst the population, often to elderly and sick patients, and the doses should not be used to assess detriment. Practice is concentrated in the countries of health-care level I, which collectively represent only one quarter of the world population, yet account for over 80% of the collective dose from all diagnostic procedures and over 50% of the total number of treatments. The global estimates for the annual frequencies of diagnostic and therapeutic procedures and the annual per caput doses from diagnostic practices are summarized in Figures VIII and IX, respectively. Detailed analyses of practice have already been given for medical and dental x rays (Table 30), diagnostic nuclear medicine (Table 46), teletherapy and brachytherapy (Table 60), and therapeutic radiopharmaceuticals (Table 71).

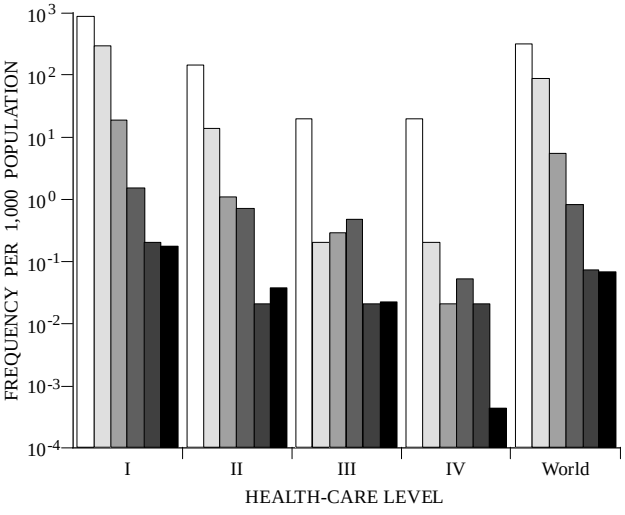

Figure VIII. Estimated global annual frequencies of medical diagnostic and therapeutic procedures (1991-1996). *The six columns in each group represent medical x rays, dental x rays, nuclear medicine (diagnosis), teletherapy, brachytherapy, and nuclear medicine (therapy), respectively.*

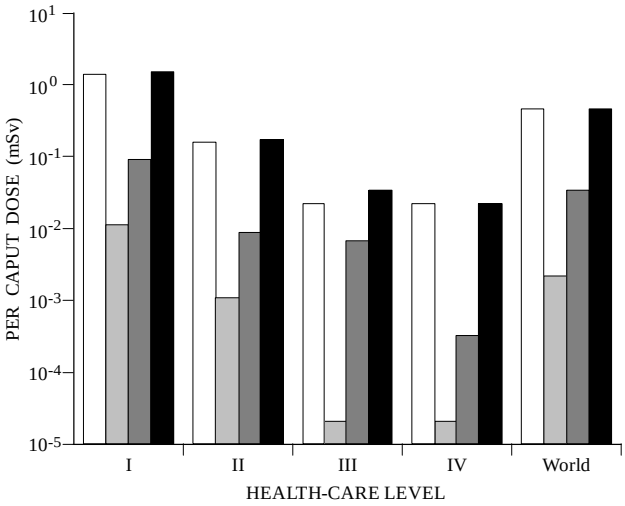

Figure IX. Estimated global annual per caput doses from medical diagnostic radiological procedures (1991-1996). *The four columns in each group represent medical x rays, dental x rays, nuclear medicine (diagnosis), and all diagnostic practices, respectively.*

210. Diagnostic exposures (2,500 million in total) outweigh the number of therapeutic exposures (5.5 million) by about 450 to 1, largely through the widespread use of x rays. Medical x rays account for 78% of this diagnostic total (at a mean rate of 330 per 1,000 population); dental x rays provide 21% (mean rate 90 per 1,000) and nuclear medicine only 1% (mean rate 5.6 per 1,000). The total collective dose from all diagnostic exposures is estimated to be about 2,500 million man Sv (corresponding to 0.4 mSv per caput); nuclear medicine provides only 6% of this total (at 0.03 mSv per caput). Over 90% of the total of radiation treatments are conducted by teletherapy or brachytherapy, with mean rates of 0.8 and 0.07 per 1,000 population, respectively; radiopharmaceuticals are used in only 7% of all treatments (with a mean rate of 0.065 per 1,000 population).

211. Notwithstanding such global average values, there are wide differences in the radiology practices between different countries (Tables 32, 34, 48, 62 and 72) and, on average, between the four levels of health-care adopted in this review (Figures VIII and IX). For example, the mean frequencies of diagnostic examinations per 1,000 population vary between the health-care levels by factors of about 50 for medical x-ray examinations, 1,500 for dental x-ray examinations and 1,000 for nuclear medicine procedures. Corresponding variations in the mean frequencies of radiation treatments amount to factors of about 30 for teletherapy, 10 for brachytherapy and more than 200 for nuclear medicine treatments. The mean per caput doses from each diagnostic practice vary between the health-care levels by factors of about 60 for medical x-ray examinations, more than 100 for dental x-ray examinations and 300 for diagnostic nuclear medicine procedures.

212. Temporal trends in the estimates of global practice in medical radiology from the various reviews undertaken by

the Committee are summarized in Table 78 for diagnostic uses and in Table 79 for therapeutic uses. Relative to the previous analysis for 1993, the world population has risen by about 10% to a total of 5,800 million in 1996 and there have been increases in the estimated annual numbers of all types of exposure and, importantly, in the per caput dose from medical x rays; the present mean effective dose per examination of 1.2 mSv is larger than the estimate of 1.0 mSv for 1985–1990. Estimates of the collective doses from diagnostic examinations with dental x rays and radiopharmaceuticals remain largely unchanged. In consequence, the estimated per caput global exposure from all diagnostic medical procedures has been revised from 0.3 to 0.4 mSv per person per year. The present estimates of the corresponding per caput dose by health-care level (with previous estimates for 1985–1990 in brackets) are as follows: 1.3 (1.1) mSv per person per year in level I, 0.15 (0.1) mSv in level II, 0.03 (0.05) mSv in level III, and 0.02 (0.05) mSv in level IV. Overall, the global annual per caput dose from diagnostic procedures worldwide is broadly similar to previous estimates made since 1982 [U3, U4, U6], although the present analysis is made on a somewhat firmer basis. Nevertheless, in general the estimates of global frequencies and doses remain fairly crude and should not be overinterpreted.

213. Further increases in the uses of medical radiations and resultant doses can be expected following changes in the patterns of health care that are being facilitated by advances in technology and economic developments. For example, increases are likely in the utilization of x rays, with in particular a growth in importance for CT, digital imaging and, with the attendant potential for deterministic effects on skin, interventional procedures; practice in nuclear medicine will be driven by the use of new and more specific radiopharmaceuticals for diagnosis and therapy, and there will be increased demand for radiotherapy owing to population ageing. In addition, further growth in medical radiology can be expected in developing countries where present facilities and services are often lacking.

214. Accordingly, there is a need for the Committee to undertake further authoritative reviews of global practice, with the systematic compilation of new national survey data, particularly from regions where knowledge is presently sparse, and the exploration of improved modeling in order to provide refined assessments of worldwide exposures. This major task will help monitor and inform on levels and trends in dose from the rapidly evolving and important practice of medical radiology, and also stimulate further assessments and critical review of practices by individual countries.

Table 1
Population distribution over the four health-care levels as used in global assessments of medical exposures

Year	*Percentage of population by health-care level*				*Global population (millions)*	*Ref.*
	I	*II*	*III*	*IV*		
1977	29	35	23	13	4 200	[U6]
1984	27	50	15	8	5 000	[U4]
1990	25	50	16	9	5 290	[U3]
1996	26	53	11	10	5 800	Present

Table 2
Physicians and dentists per million population (1991-1996)
Data from UNSCEAR Survey of Medical Radiation Usage and Exposures unless otherwise indicated

Country / area	*Population (thousands)*	*Number per million population*		
		All physicians	*Physicians conducting radiological procedures*	*Dentists*
Health-care level I				
Albania	3 400	1 370 [a]	50	340 [a]
Argentina	35 672	2 489	22	614
Armenia	3 638	-	- [c]	-
Australia	17 684	2 590	107	515
Austria	8 000	3 008 [b]	-	90 [b]
Bahrain	570	1 290 [a]	-	130 [a]
Belarus	10 312	4 102	113	358
Belgium	10 000	3 360 [a]	113	660 [a]
Bulgaria	8 492	3 249	94	674
Canada	27 952	1 891	74	515
Cayman Islands	34	1 559	29	353
China, Taiwan Province	21 743	1 183	30	348
Croatia	4 760	2 056	93	382
Cuba	10 906	3 010 [a]	3	590 [a]
Cyprus	651	2 540	71	834
Czech Republic	10 363	3 371	141	592
Denmark	5 100	3 039	59	1 353
Ecuador	13 000	2 000	15	615
Estonia	1 500	-	-	-
Finland	5 117	3 261	111	923
France	57 660	3 000 [a]	119 [d]	670 [a]
Germany	81 500	3 279	405	726
Greece	10 500	3 810	171	1 048
Hungary	10 300	3 592	126	473
Ireland	3 626	3 000	77	452
Israel	5 664	2 415 [b]	-	497 [b]
Italy	56 411	4 750 [a]	106 [d]	190 [a]
Japan	125 034	1 766	94	633
Kazakhstan	16 820	-	-	-
Kuwait	1 691	1 959	56	384
Kyrgyzstan	4 469	-	-	-
Latvia	2 504	-	-	-
Lebanon	4 000	1 825	50	875
Lithuania	3 710	4440	155	461
Luxembourg	407	2 086	246	499
Netherlands	15 000	3 558	87	467
New Zealand	3 643	2 196	49	538
Norway	4 325	3 554	88	1 208
Panama	2 674	1 751	21	440
Poland	38 601	2 140 [a]	39 [d]	480 [a]
Portugal [F11]	9 860	2 870	54	65 [b]
Qatar	540	1 958 [b]	-	288 [b]
Republic of Moldova	4 444	-	-	-
Romania	22 681	1 771	38	267
Russian Federation	148 300	4 100	100	480 [a]

Table 2, continued

Country / area	*Population (thousands)*	*Number per million population*		
		All physicians	*Physicians conducting radiological procedures*	*Dentists*
Slovakia	5 325	3 335	83	389
Slovenia	1 987	2 139	63	568
South Africa	42 393	-	-	-
Spain	39 674	3 820 [a]	-	270 [a]
Sweden	8 800	2 841	125	1 364
Switzerland	7 097	3 839	-	641
Ukraine	52 464	-	95	-
United Arab Emirates	2 390	2 056	31	255
United Kingdom	58 200	1 660	41	388
United States [M2]	260 000	2 381	92	-
Uruguay	3 168	1 881 [b]	3	752 [b]
Uzbekistan	23 209	-	-	-
Venezuela	21 377	1 282 [b]	5	-
Average for level		2 784	106	526
Health-care level II				
Algeria	28 784	940 [a]	-	290 [a]
Antigua and Barbuda	65	908 [a]	31	200 [a]
Bahamas	272	900 [b]	-	129 [b]
Barbados	250	1 176 [a]	56	132 [a]
Belize	189	450 [a]	-	63 [a]
Bolivia	7 238	390 [a]	2	50 [a]
Bosnia and Herzegovina	3 628	-	-	-
Brazil	150 000	1 111	222	667
Chile	13 994	1 060 [a]	3	400 [a]
China	1 196 360	839 [b]	-	30 [b]
Colombia	34 545	940 [a]	1	440 [a]
Costa Rica	3 500	880 [a]	-	-
Dominica	80	475 [a]	0	50 [a]
Dominican Republic	7 684	1 070 [a]	1	100 [a]
El Salvador	5 530	640 [a]	1	160 [a]
Grenada	95	537 [a]	11	42 [a]
Honduras	5 494	790 [a]	0.4	90 [a]
India	944 580	410 [a]	-	10 [a]
Jordan	5 198	1 540 [a]	-	356 [a]
Libyan Arab Jamahiriya	5 225	1 040 [a]	-	150 [a]
Malaysia	19 570	451	5	80 [a]
Mauritius	1 129	850 [a]	-	130 [a]
Mexico	92 718	392	33	17
Nicaragua	4 008	500 [a]	1	100 [a]
Oman	2 256	852	13	37
Pakistan	140 000	500 [a]	-	20 [a]
Paraguay	4 703	630 [a]	1	250 [a]
Peru	23 500	979	11	240
Philippines	73 000	1 160	8	486
Puerto Rico	3 818	1 190 [b]	3	217 [b]
Saint Kitts and Nevis	36	1 194 [a]	0	306 [a]
Saint Lucia	140	421 [a]	7	64 [a]
Saint Vincent and the Grenadines	110	500 [a]	9	55 [a]
Trinidad and Tobago	1 292	730 [a]	3	90 [a]
Tunisia	9 000	944	19	60
Turkey	63 898	1 036	35	261
Average for level		695	76	87
Health-care level III				
Afghanistan	20 883	130 [a]	-	20 [a]
Congo	2 668	280 [a]	-	20 [a]
Egypt	63 271	185 [b]	-	158 [b]
Ghana	17 832	241	0.3	2 [a]
Guatamala	9 715	250 [a]	0.6	30 [a]
Guyana	838	124 [b]	-	11 [b]
Haiti	7 035	140 [a]	-	10 [a]
Jamaica	2 429	140 [a]	0.4	20 [a]
Madagascar	14 000	400	14	50
Morocco	26 702	205 [b]	6	59

Table 2, continued

Country / area	*Population (thousands)*	*Number per million population*		
		All physicians	*Physicians conducting radiological procedures*	*Dentists*
Namibia	1 575	220 [a]	-	30 [a]
Nigeria	115 020	170 [a]	-	10 [a]
Sudan	26 000	409	3	39
Suriname	432	-	-	-
Zimbabwe	11 439	130 [a]	-	10 [a]
Average for level		208	5	49
Health-care level IV				
Angola	11 185	40 [a]	-	1 [a]
Cameroon	13 560	80 [a]	-	4 [a]
Ethiopia	60 000	34	0.02	-
Kenya	27 800	50 [a]	-	10 [a]
Liberia	2 245	-	-	-
Mozambique	17 796	30 [a]	-	1 [a]
Nepal	22 000	60 [a]	-	0 [a]
Senegal	8 532	60 [a]	-	10 [a]
Uganda	20 256	40 [a]	-	1 [b]
United Rep. of Tanzania	28 400	45	0.4	1
Average for level		45	0.1	3

a Data from reference [W20].
b Data from reference [S37].
c No data available.
d Data from reference [R19].

The entries in this Table are qualified as follows:

Albania: Data on physicians conducting radiological procedures from reference [C28].
Argentina: Data for physicians conducting radiological procedures refer only to practice in nuclear medicine, teletherapy, and brachytherapy.
Barbados: Data for physicians conducting radiological procedures from reference [B43].
Belgium: Data for physicians conducting radiological procedures from reference [C26].
Brazil: Data for Paraná State (with a population of 9 million and a social and economic profile above the average for Brazil).
Dominica: Data for physicians conducting radiological procedures from reference [B43].
Ghana: Data on physicians from reference [S38].
Russia: Number of dentists refers to data for USSR in 1990 from reference [W20].
Trinidad and Tobago: Data for physicians conducting radiological procedures refer only to radiotherapy practice from reference [B43].
Ukraine: Data on physicians conducting radiological procedures from reference [W33].

Bolivia, Chile, Colombia, Cuba, Dominican Rep., El Salvador, Guatemala, Honduras, Jamaica, Nicaragua, Paraguay, Puerto Rico, Trinidad and Tobago, Uruguay, and Venezuela:
Data for physicians conducting radiological procedures refer only to radiotherapy practice from reference [B43].

Antigua, Grenada, Saint Kitts and Nevis, Saint Lucia, Saint Vincent and the Grenadines:
Data for physicians conducting radiological procedures in public sector from reference [B43].

Table 3
Diagnostic imaging equipment (1991-1996)
Data from UNSCEAR Survey of Medical Radiation Usage and Exposures unless otherwise indicated

Country / area	*X-ray generators*			*CT scanners*	*MRI scanners*	*Nuclear medicine equipment*		
	Medical	*Mammography*	*Dental*			*Gamma cameras*	*Rectilinear scanners*	*PET scanners*
Health-care level I								
Albania [C28]	-	-	-	1	0	-	-	-
Argentina	12 000	-	-	-	-	311	122	1
Australia	-	258	-	332	42	-	-	-
Belarus	2 400	3	92	14	4	15	0	0
Belgium	-	-	-	210	36	-	-	-
Bulgaria	1 813	26	431	22	1	12	37	0
Canada	9 725	565	36 978	223	35	500	-	5
Cayman Islands	6	0	0	0	0	0	0	0
China, Taiwan Province	3 662	61	6 212	293	47	87	2	2
Croatia	620	21	250	29	2	6	3	0
Cuba	1 000	-	-	10	4	9	-	-
Cyprus	72	13	550	8	2	4	0	0
Czech Republic	2 380	68	3 100	62	7	80	35	0
Denmark	1 225	55	4 970	50	18	58	0	3
Ecuador	619	26	771	27	8	12	7	0
Estonia [S29]	392	21	107	3	1	2	-	-
Finland	1 600	192	4 746	60	22	58	0	1
France [A14]	18 312	2 431	36 386	561	146	350	43	-
Germany	50 000	3 550	74 000	1 400	400	850	50	40
Greece	1 200	170	7 000	150	20	150	15	0
Hungary	1 170	46	350	54	13	53	34	1
Ireland	360	29	1 305	26	6	23	0	0
Israel [S48]	-	-	-	42	-	-	-	-
Italy	9 946	1 354	-	550	210	315	20	5
Japan	77 000	1 461 [a]	57 515	7 959	1 559	1 387	-	33
Kuwait	217	11	155	13	2	19	0	0
Lebanon	400	50	400	45	5	26	-	-
Lithuania	847	21	308	15	0	4	11	0
Luxembourg	70	10	313	9	1	4	0	0
Netherlands	3 000	130	7 500	120	55	180	-	1
New Zealand	734	66	1 790	30	6	22	0	0
Norway	2 000	60	6 000	75	15	43	4	0
Panama	416	16	0	10	2	7	0	0
Poland [R25]	-	-	-	75	11	-	-	-
Qatar	38	2	7	2	1	2	0	0
Romania	2 529	37	900	35	1	-	-	-
Russian Federation	27 340	1 210	6 730	320	100	300	-	-
Slovakia	1 351	48	551	31	3	17	3	1
Slovenia	270	15	259	9	2	13	0	0
Spain	6 371	-	-	226	131	190	-	-
Sweden	1 400	170	13 500	115	50	90	1	5
Switzerland	8 419	240	8 583	187	99	110	-	7
Ukraine [W33]	-	-	-	70	18	-	-	-
United Arab Emirates	342	22	790	17	2	9	0	0
United Kingdom	-	258	20 350	350	140	365	7	5
United States	55 177	10 022	-	6 800	3 500	2 000	-	-
Uruguay	350	-	-	-	-	-	-	-
Venezuela [B33]	3 000	-	-	-	-	-	-	-
Health-care level II								
Algeria [V9]	-	-	-	8	1	7	-	-
Antigua and Barbuda [B33, B43]	4	-	-	-	0	0	0	0
Bahamas [B33]	5	-	-	-	-	-	-	-
Barbados [B33]	20	2	1	2	0	-	-	-
Belize [B33]	12	-	-	-	-	-	-	-
Bolivia [B33]	1 458	-	-	-	-	-	-	-
Brazil	16 667	-	75 000	800	-	150 [a]	-	0 [a]
Chile [B33]	1 350	-	-	-	-	-	-	-
China	65 522	393	1 633	2 750	242	287	362	3
Colombia [B33]	1 500	-	-	-	-	-	-	-
Costa Rica [B33]	190	-	-	-	-	-	-	-
Dominica [B33, B43]	6	0	5	0	0	0	0	0

Table 3 (continued)

Country / area	*X-ray generators*			*CT scanners*	*MRI scanners*	*Nuclear medicine equipment*		
	Medical	*Mammography*	*Dental*			*Gamma cameras*	*Rectilinear scanners*	*PET scanners*
Dominican Republic [B33]	180	-	-	-	-	-	-	-
El Salvador [B33]	136	-	-	-	-	-	-	-
Grenada [B33, B43]	3	0	-	0	0	0	0	0
Honduras [B33]	87	-	-	-	-	-	-	-
India [R20]	-	-	-	-	40	-	-	-
Libyan Arab Jamahiriya	-	-	-	14	2	4	-	-
Malaysia	1 270	23	-	38	8	8	-	-
Mexico	1 469	10	635	56	2	26	0	0
Nicaragua [B33]	50	-	-	-	-	-	-	-
Oman	94	2	12	7	1	2	0	0
Paraguay	100	-	-	-	-	-	-	-
Peru	1 400	40	1 800	30	5	10	2	0
Philippines	2 079	56	140	95	6	27	1	0
Saint Kitts and Nevis [B33, B43]	3	-	-	0	0	0	0	0
Saint Lucia	14	-	0	1	0	0	0	0
Saint Vincent and the Grenadines [B33, B43]	4	-	-	0	0	0	0	0
Trinidad and Tobago	20	-	-	-	-	-	-	-
Tunisia	538	23	400	24	1	8	0	0
Turkey	5 000	120	10 000	173	35	100	6	0
Health-care level III								
Ghana	121	4	-	3	-	-	-	-
Guatamala [B33]	95	-	-	-	-	-	-	-
Haiti	20	-	-	-	-	-	-	-
Jamaica	30	-	-	-	-	-	-	-
Madagascar	66	1	300	1	-	1	-	0
Morocco	3272	6	411	29	7	5	4	-
Sudan	344	4	47	4	0	3	1	0
Health-care level IV								
Ethiopia	-	-	-	-	-	1	1	0
Kenya [B41]	-	-	-	4	2	2	-	-
United Rep. of Tanzania	125	4	2	2	0	1	0	0

a These revised data were received by the Committee after completion of the global analysis.

The entries in this Table are qualified as follows:

Argentina: Data for medical x-ray units from reference [B33]. Total for gamma cameras includes 100 SPECT scanners.
Belgium: Data for CT scanners from reference [C26]. Data for MRI scanners from reference [R33].
Brazil: Except for data on gamma cameras and PET scanners, numbers extrapolated from data for Paraná State (with a population of 9 million and a social and economic profile above the average for Brazil). Estimate for national total of CT scanners from M. T. Carlos, University of Rio de Janeiro (1998).
Canada: Total for dental x-ray generators extrapolated from data for province of Alberta (representing about 9.5% of population); totals for medical x-ray generators and gamma cameras extrapolated from data for province of Manitoba (representing about 4% of population).
Cuba: Data for medical x-ray units from reference [B33]. Other data from reference [H32].
Ghana: Data from reference [S38]. Nuclear medicine conducted only at Korle Bu Teaching Hospital [A16].
Italy: Data on x-ray generators (medical and mammography), and CT and MRI scanners from reference [B40]; total for medical x-ray generators includes dental equipment.
Oman: Total for dental x-ray generators refers to panoramic equipment.
Philippines: Totals shown for medical and dental x-ray generators refer to facilities and not individual machines.
Russian Federation: Data for MRI scanners and gamma cameras from reference [W33].
Saint Lucia: Data from references [B33] and [B43]. Total for dental x-ray generators refers to public sector.
Spain: Data from reference[B40]. Total for medical x-ray generators includes dental equipment. Total for gamma cameras includes public sector only.
Turkey: Data for CT scanners from reference [S47]; 60% of the total operate in the private sector.
United States: Data from reference [B40]. Total for medical x-ray generators includes dental equipment. Total for gamma cameras includes all nuclear medicine imaging equipment.

Haiti, Jamaica, Paraguay, Trinidad and Tobago, Uruguay: Estimated number of medical x-ray generators from reference [B33].

Table 4
Diagnostic imaging equipment per million population (1991-1996)
Based on data and qualifications from Table 3

Country / area	*X-ray generators*			*CT scanners*	*MRI scanners*	*Nuclear medicine equipment*		
	Medical	*Mammography*	*Dental*			*Gamma cameras*	*Rectilinear scanners*	*PET scanners*
Health-care level I								
Albania	-	-	-	0.3	0	-	-	-
Argentina	336	-	-	-	-	8.72	3.42	0.03
Australia	-	14.6	-	18.8	2.37	-	-	-
Belarus	233	0.3	9	1.4	0.39	1.45	0	0
Belgium	-	-	-	21.0	3.60	-	-	-
Bulgaria	213	3.1	51	2.6	0.12	1.41	4.36	0
Canada	348	20.2	1 323	8.0	1.25	17.9	-	0.18
Cayman Islands	176	0	0	0	0	0	0	0
China, Taiwan Province	168	2.8	286	13.5	2.16	4.00	0.09	0.09
Croatia	130	4.4	53	6.1	0.42	1.26	0.63	0
Cuba	92	-	-	0.9	0.37	0.83	-	-
Cyprus	111	20.0	844	12.3	3.07	6.14	0	0
Czech Republic	230	6.6	299	6.0	0.68	7.72	3.38	0
Denmark	240	10.8	975	9.8	3.53	11.4	0	0.59
Ecuador	48	2.0	59	2.1	0.62	0.92	0.54	0
Estonia	261	14.0	71	2.0	0.67	1.33	-	-
Finland	313	37.5	928	11.7	4.30	11.3	0	0.20
France	318	42.2	631	9.7	2.53	6.07	0.75	-
Germany	614	43.6	908	17.2	4.91	10.4	0.61	0.49
Greece	114	16.2	667	14.3	1.90	14.3	1.43	0
Hungary	114	4.5	34	5.2	1.26	5.15	3.30	0.10
Ireland	99	8.0	360	7.2	1.65	6.34	0	0
Israel	-	-	-	7.4	-	-	-	
Italy	176	24.0	-	9.8	3.72	5.58	0.35	0.09
Japan	616	11.7	460	63.7	12.5	11.1	-	0.26
Kuwait	128	6.5	92	7.7	1.18	11.2	0	0
Lebanon	100	12.5	100	11.3	1.25	6.50	-	-
Lithuania	228	5.7	83	4.0	0	1.08	2.97	0
Luxembourg	172	24.6	770	22.1	2.46	9.84	0	0
Netherlands	200	8.7	500	8.0	3.67	12.0	-	0.07
New Zealand	202	18.1	491	8.2	1.65	6.04	0	0
Norway	462	13.9	1 387	17.3	3.47	9.94	0.92	0
Panama	156	6.0	0	3.7	0.75	2.62	0	0
Poland	-	-	-	1.9	0.28	-	-	-
Qatar	70	3.7	13	3.7	1.85	3.70	0	0
Romania	112	1.6	40	1.5	0.04	-	-	-
Russian Federation	184	8.2	45	2.2	0.67	2.02	-	-
Slovakia	254	9.0	103	5.8	0.56	3.19	0.56	0.19
Slovenia	136	7.6	130	4.5	1.01	6.54	0	0
Spain	161	-	-	5.7	3.30	4.79	-	-
Sweden	159	19.3	1 534	13.1	5.68	10.2	0.11	0.57
Switzerland	1 186	33.8	1 209	26.4	14.0	15.5	-	0.99
Ukraine	-	-	-	1.3	0.34	-	-	-
United Arab Emirates	143	9.2	331	7.1	0.84	3.77	0	0
United Kingdom	-	4.4	350	6.0	2.41	6.27	0.12	0.09
United States	212	38.6	-	26.2	13.5	7.69	-	-
Uruguay	110	-	-	-	-	-	-	-
Venezuela	140	-	-	-	-	-	-	-
Average	293	23.7	440	17.4	5.71	7.19	0.92	0.20
Health-care level II								
Algeria	-	-	-	0.28	0.03	0.24	-	-
Antigua and Barbuda	62	-	-	-	0	0	0	0
Bahamas	18	-	-	-	-	-	-	-
Barbados	80	8.0	4.0	8.00	0	-	-	-
Belize	63	-	-	-	-	-	-	-
Bolivia	201	-	-	-	-	-	-	-
Brazil	111	-	500	5.33	-	1.0	-	-
Chile	96	-	-	-	-	-	-	-
China	55	0.33	1.4	2.30	0.20	0.24	0.30	0.003
Colombia	43	-	-	-	-	-	-	-
Costa Rica	54	-	-	-	-	-	-	-

Table 4 (continued)

Country / area	*X-ray generators*			*CT scanners*	*MRI scanners*	*Nuclear medicine equipment*		
	Medical	*Mammography*	*Dental*			*Gamma cameras*	*Rectilinear scanners*	*PET scanners*
Dominica	75	0	63	0	0	0	0	0
Dominican Republic	23	-	-	-	-	-	-	-
El Salvador	25	-	-	-	-	-	-	-
Grenada	32	0	-	0	0	0	0	0
Honduras	16	-	-	-	-	-	-	-
India	-	-	-	-	0.04	-	-	-
Libyan Arab Jamahiriya	-	-	-	2.7	0.38	0.77	-	-
Malaysia	65	1.2	-	1.9	0.41	0.41	-	-
Mexico	16	0.11	6.9	0.60	0.02	0.28	0	0
Nicaragua	12	-	-	-	-	-	-	-
Oman	42	0.89	5.3	3.1	0.44	0.89	0	0
Paraguay	21	-	-	-	-	-	-	-
Peru	60	1.7	77	1.3	0.21	0.43	0.09	0
Philippines	28	0.77	1.9	1.3	0.08	0.37	0.01	0
Saint Kitts and Nevis	83	-	-	0	0	0	0	0
Saint Lucia	100	-	0	7.1	0	0	0	0
Saint Vincent and the Grenadines	36	-	-	0	0	0	0	0
Trinidad and Tobago	15	-	-	-	-	-	-	-
Tunisia	60	2.6	44	2.7	0.11	0.89	0	0
Turkey	78	1.9	157	2.9	0.55	1.56	0.09	0
Average	58	0.45	56	2.4	0.14	0.32	0.25	0.002
Health-care level III								
Ghana	6.8	0.22	-	0.17	-	-	-	-
Guatamala	9.8	-	-	-	-	-	-	-
Haiti	2.8	-	-	-	-	-	-	-
Jamaica	12.4	-	-	-	-	-	-	-
Madagascar	4.7	0.07	21.4	0.07	-	0.07	-	0
Morocco	123	0.22	15.4	1.09	0.26	0.19	0.15	-
Sudan	13.2	0.15	1.8	0.15	0	0.12	0.04	0
Average	38	0.18	11.4	0.44	0.13	0.13	0.09	0
Health-care level IV								
Ethiopia	-	-	-	-	-	0.02	0.02	0
Kenya	-	-	-	0.14	0.07	0.07	-	-
United Rep. of Tanzania	4.4	0.14	0.07	0.07	0	0.04	0	0
Average	4.4	0.14	0.07	0.11	0.04	0.03	0.01	0

Table 5
Radiotherapy equipment (1991-1996)
Data from UNSCEAR Survey of Medical Radiation Usage and Exposures unless otherwise indicated

Country / area	Teletherapy units				Brachytherapy afterloading units				Clinical therapy facilities	
	X-ray	Radio-nuclide [a]	LINACs	SRS [b]	Manual [c]	Remote LDR [d]	Remote HDR [e]	Total	Neutrons	Heavy ions
Health-care level I										
Albania [D27]	-	3 (0)	0	0	-	-	-	-	-	-
Argentina	-	103(2)	41	1	74	0	3	77	0	0
Armenia [D27]	-	4	0	0	-	-	-	-	-	-
Australia	40	2 (0)	77	3	20	16	2	38	-	-
Belarus	15	29 (0)	4	0	0	2	12	14	-	-
Belgium	14	16	34	-	16	15	10	41	-	-
Bulgaria	35	12 (0)	0	0	9	0	1	10	0	0
Canada	10	44 (0)	107	0	30	28	20	78	0	1
Cayman Islands	0	0	0	0	0	0	0	0	0	0
China, Taiwan Province	3	23 (0)	56	1	6	0	36	42	0	0
Croatia	10	14 (8)	2	0	2	0	0	2	0	1
Cuba	30	9 (0)	1	-	8	4	-	12	-	-
Cyprus	2	2 (0)	0	0	1	0	0	1	0	0
Czech Republic	48	59 (23)	18	1	21	6	6	33	-	-
Denmark	5	1 (0)	25	0	1	3	3	7	0	0
Ecuador	7	9 (0)	0	0	2	2	0	4	0	0
Estonia	-	3	2	-	-	3	-	3	-	-
Finland	11	1 (0)	23	0	1	3	7	11	0	0
France [A14]	138	133	223	1	-	173	21	194	3	-
Germany	800	160	230	1	-	-	-	190	2	0
Greece	3	24 (0)	14	2	0	0	10	10	0	0
Hungary	25	12 (2)	10	1	0	0	11	11	0	0
Ireland	3	3 (0)	8	0	1	1	2	4	0	0
Japan	0	298 (0)	564	-	-	-	-	219	-	2
Kazakhstan	-	1	2	-	-	1	-	1	-	-
Kuwait	2	2 (0)	1	0	0	1	0	1	-	-
Kyrgyzstan	-	2	1	-	-	4	-	4	-	-
Latvia	-	5	5	-	-	3	-	3	-	-
Lebanon	-	11 (6)	6	7	-	-	-	-	-	-
Lithuania	9	12 (0)	0	0	1	0	5	6	1	-
Luxembourg	0	0	0	0	0	0	0	0	0	0
Netherlands	34	0	60 [f]	1	-	25 [f]	12 [f]	37 [f]	1	0
New Zealand	11	2 (1)	14	1	6	1	1	8	0	0
Norway	30	1 (0)	19	1	1	0	3	4	0	0
Panama	2	3 (0)	0	0	2	0	0	2	0	0
Poland	-	17	24	-	3	12	-	15	-	-
Qatar	0	0	0	0	0	0	0	0	0	0
Rep. of Moldova [D27]	-	3	0	0	-	-	-	-	-	-
Romania	140	21 (0)	3	0	2	4	4	10	0	0
Russian Federation [D27]	-	-	5	-	-	-	-	-	-	-
Slovakia	25	21 (5)	5	0	2	4	9	15	0	0
Slovenia	5	2 (0)	3	0	3	2	0	5	0	0
South Africa	-	23	24	-	5	12	-	17	-	-
Sweden	26	3 (0)	56	1	0	7	5	12	0	1
Switzerland	77	12(0)	38	1	0	5	14	19	-	1
Ukraine [D27]	-	10	1	-	-	-	-	-	-	-
United Arab Emirates	0	2 (0)	4	1	2	0	2	4	0	0
United Kingdom	70	15 (0)	150	1	3	30	20	53	0	1
United States	-	504	1893	-	-	-	-	-	-	-
Uruguay [B43]	-	10 (0)	3	-	0	0	0	0	-	-
Uzbekistan [D27]	-	-	1	-	-	-	-	-	-	-
Venezuela	-	24 (0)	15	-	30	2	0	32	-	-
Health-care level II										
Algeria [D27]	-	15 (0)	8	-	5	7	-	12	-	-
Antigua and Barbuda [B33, B43]	0	0	0	0	0	0	0	0	0	0
Bahamas [B43]	0	0	0	0	0	0	0	0	0	0
Barbados	-	1 (0)	0	-	2	1	-	3	-	-
Belize [B43]	0	0	0	0	0	0	0	0	0	0
Bolivia	0	0	0	0	0	0	0	0	0	0
Bosnia and Herzegovina [D27]	-	2	1	-	-	-	-	-	-	-

Table 5 (continued)

Country / area	*Teletherapy units*				*Brachytherapy afterloading units*				*Clinical therapy facilities*	
	X-ray	*Radio-nuclide* [a]	*LINACs*	*SRS* [b]	*Manual* [c]	*Remote LDR* [d]	*Remote HDR* [e]	*Total*	*Neutrons*	*Heavy ions*
Brazil	169 [f]	126 [f]	68 [f]	3 [f]	100 [f]	- [f]	22 [f]	124	0	0
Chile	-	21 (0)	14	-	19	1	-	20	-	-
China	225	541(40)	282	36	0	0	309	309	1	0
Colombia	-	28 (0)	11	-	15	7	-	22	-	-
Costa Rica	2	3 (0)	0	-	7	0	0	7	-	-
Dominica [B43]	0	0	0	0	0	0	0	0	0	0
Dominican Republic	-	8 (0)	1	-	3	1	-	4	0	0
El Salvador	-	3 (0)	0	-	9	0	0	9	-	-
Grenada [B43]	0	0	0	0	0	0	0	0	0	0
Honduras	-	2 (0)	0	-	2	0	0	2	-	-
Jordan	1	2(0)	3	-	0	1	0	1	0	0
Libyan Arab Jamahiriya	2	3	-	-	-	-	-	-	-	-
Malaysia	1	8 (1)	7	0	7	0	0	7	0	0
Mauritius [D27]	-	2	2	-	2	-	-	2	-	-
Mexico	7	92 (0)	24	0	65	7	-	72	0	0
Nicaragua	-	1 (0)	0	-	5	0	0	5	-	-
Oman	0	0	0	0	0	0	0	0	0	0
Pakistan [L57]	-	2 (0)	1	-	-	-	-	-	-	-
Paraguay [B43]	-	4 (0)	3	-	0	0	0	0	-	-
Peru	10	9 (0)	3	-	25	0	0	25	-	-
Philippines	2	12 (0)	3	2	1	2	2	5	0	0
Puerto Rico	-	2	2	-	0	0	0	0	-	-
Saint Kitts and Nevis [B43]	0	0	0	0	0	0	0	0	0	0
Saint Lucia [B43]	0	0	0	0	0	0	0	0	0	0
Saint Vincent and the Grenadines [B43]	0	0	0	0	0	0	0	0	0	0
Trinidad & Tobago	-	2 (0)	0	-	2	0	0	2	-	-
Tunisia	2	7 (0)	1	-	5	10	-	15	0	0
Turkey	22	41 (0)	20	3	6	3	9	18	0	0
Health-care level III										
Afghanistan [L57]	0	0	0	0	0	0	0	0	0	0
Congo [D27]	-	1	0	0	-	-	-	-	-	-
Egypt	-	13	13	-	4	2	-	6	-	-
Ghana	-	2	0	0	4	4	-	8	-	-
Guatamala	-	6 (0)	0	-	8	1	0	9	-	-
Guyana [D27]	-	0	0	0	0	0	0	0	-	-
Haiti [B33]	-	2 (0)	0	-	-	-	-	-	-	-
Jamaica [B43]	-	2 (0)	0	-	0	0	0	0	-	-
Madagascar	1	1	-	-	-	-	-	-	-	-
Morocco	1	9 (4)	1	-	-	-	-	-	-	-
Namibia [D27]	-	1	0	0	-	-	-	-	-	-
Nigeria	-	5	0	0	2	3	-	5	-	-
Sudan	1	3 (0)	1	0	0	2	1	3	0	0
Suriname [D27]	-	0	0	0	0	0	0	0	-	-
Zimbabwe [B42]	-	3 (0)	3	-	1	2	-	3	0	0
Health-care level IV										
Angola [D27]	-	1	0	0	-	-	-	-	-	-
Cameroon	-	2	0	0	2	3	-	5	-	-
Ethiopia	-	1	0	0	0	1	-	1	-	-
Kenya [B41]	-	3 (0)	0	0	2	1	1	4	0	0
Liberia [D27]	-	1	0	0	-	-	-	-	-	-
Mozambique [D27]	-	1	0	0	-	-	-	-	-	-
Nepal [D22]	0	1 (0)	0	0	0	0	0	0	0	0
Senegal [D27]	-	1	0	0	-	-	-	-	-	-
Uganda [D27]	-	2	0	0	1	-	-	1	-	-
United Rep. of Tanzania	1	2 (1)	0	0	0	0	1	1	0	0

a Includes both ^{60}Co and ^{137}Cs units; total of the latter type shown in brackets.
b Stereotactic radiosurgery; includes units based on radionuclides (Gammaknife), Linacs and other specialist radiation sources.
c Number of treatment rooms.
d Remote low dose rate.
e Remote high dose rate.
f These revised data were received by the Committee after completion of the global analysis.

Table 5 (continued)

The entries in this Table are qualified as follows:

Afghanistan: No radiotherapy or oncology services in country [L57].
Algeria: Total for LDR refers to all types of remote unit.
Belgium: Total for manual afterloading brachytherapy units refers to the sum, over all centres performing this technique, of the number of diferent radionuclides in use at each centre.
Cameroon: Data from reference [D27]. Total for LDR refers to all types of remote unit.
Canada: Total for x-ray teletherapy units extrapolated from data for province of Alberta (representing about 9.5% of population). 77 of the 107 Linacs operate above 10 MeV. Data for manual and remote-HDR brachytherapy afterloading units refer to number of licenses issued by Atomic Energy Control Board of Canada for practice; data for remote-LDR units refer to number of devices listed on licenses. Heavy ion facility refers to proton therapy.
Costa Rica: Data for ^{60}Co units and Linacs from reference [B33]. Data for x-ray teletherapy units from reference [I25]. Data for brachytherapy afterloading units from reference [D27].
Croatia: Heavy ion facility refers to betatron.
Egypt: Data from reference [D27]. Total for LDR refers to all types of remote unit.
Estonia: Data from reference [D27]. Total for LDR refers to all types of remote unit.
Ethopia: Data from reference [D27]. Total for LDR refers to all types of remote unit.
Ghana: Data from reference [D27]. Total for LDR refers to all types of remote unit.
Kazakstan: Data from reference [D27]. Total for LDR refers to all types of remote unit.
Kyrgyztan: Data from reference [D27]. Total for LDR refers to all types of remote unit.
Latvia: Data from reference [D27]. Total for LDR refers to all types of remote unit.
Mexico: All data from reference [D27], except in relation to x-ray teletherapy units. Total for LDR refers to all types of remote unit.
Nigeria: Data from reference [D27]. Total for LDR refers to all types of remote unit.
Pakistan: Data for IRNUM, Peshawar, North-West Frontier Province (serving population of 200 million including Afghanistan) [L57].
Poland: Data from reference [D27]. Total for LDR refers to all types of remote unit.
South Africa: Data from reference [D27]. Total for LDR refers to all types of remote unit.
Sweden: Heavy ion facility refers to the Svedberg Laboratory, Uppsala (180 MeV protons).
Tunisia: Data for brachytherapy afterloading units from reference [D27]. Total for LDR refers to all types of remote unit.
United Kingdom: Heavy ion facility refers to the use of protons at the Clatterbridge Centre for Oncolgy.
United States: Data for 1990 from reference [I23].
Zimbabwe: Data for brachytherapy afterloading units from reference [D27]. Total for LDR refers to all types of remote unit.

Barbados, Bolivia, Chile, Colombia, Cuba, Dominican Republic, Guatemala, Puerto Rico and Venezuela:
Data from reference [B43]. In relation to brachytherapy afterloading equipment, total for manual refers to number of sources and total for LDR refers to all types of remote unit.

El Salvador, Honduras, Nicaragua, Honduras, Tiniidad and Tobago:
Data from reference [B43]. In relation to brachytherapy afterloading equipment, total for manual refers to number of sources.

Table 6
Radiotherapy equipment per million population (1991–1996)
Based on data and qualifications from Table 5

Country / area	*Teletherapy units*			*Brachytherapy afterloading units*
	X-ray	*Radionuclide*	*LINACs*	
Health-care level I				
Albania	–	0.88	0	–
Argentina	–	2.89	1.15	2.16
Armenia	–	1.10	0	–
Australia	2.26	0.11	4.35	2.15
Belarus	1.45	2.81	0.39	1.36
Belgium	1.40	1.60	3.40	4.10
Bulgaria	4.12	1.41	0	1.18
Canada	0.36	1.57	3.83	2.79
Cayman Islands	0	0	0	0
China, Taiwan Province	0.14	1.06	2.58	1.93
Croatia	2.10	2.94	0.42	0.42
Cuba	2.75	0.83	0.09	1.10
Cyprus	3.07	3.07	0	1.54
Czech Republic	4.63	5.69	1.74	3.18
Denmark	0.98	0.20	4.90	1.37
Ecuador	0.54	0.69	0	0.31
Estonia	–	2.00	1.33	2.00
Finland	2.15	0.20	4.49	2.15
France	2.39	2.31	3.87	3.36
Germany	9.82	1.96	2.82	2.33
Greece	0.29	2.29	1.33	0.95
Hungary	2.43	1.17	0.97	1.07
Ireland	0.83	0.83	2.21	1.10
Japan	0	2.38	4.51	1.75
Kazakhstan	–	0.06	0.12	0.06
Kuwait	1.18	1.18	0.59	0.59
Kyrgyzstan	–	0.45	0.22	0.90
Latvia	–	2.00	2.00	1.20
Lebanon	–	2.75	1.75	–
Lithuania	2.43	3.23	0	1.62
Luxembourg	0	0	0	0
Netherlands	2.27	0	4.00	2.47
New Zealand	3.02	0.55	3.84	2.20
Norway	6.94	0.23	4.39	0.92
Panama	0.75	1.12	0	0.75
Poland	–	0.44	0.62	0.39
Qatar	0	0	0	0
Republic of Moldova	–	0.68	0	–
Romania	6.17	0.93	0.13	0.44
Russian Federation	–	–	0.03	–
Slovakia	4.70	3.94	0.94	2.82
Slovenia	2.52	1.01	1.51	2.52
South Africa	–	0.54	0.57	0.40
Sweden	2.95	0.34	6.36	1.36
Switzerland	10.9	1.69	5.35	2.68
Ukraine	–	0.19	0.02	–
United Arab Emirates	0	0.84	1.67	1.67
United Kingdom	1.20	0.26	2.58	0.91
United States	–	1.94	7.28	–
Uruguay	–	3.16	0.95	0
Uzbekistan	–	–	0.04	–
Venezuela	–	1.12	0.70	1.50
Average	2.84	1.56	3.04	1.69
Health-care level II				
Algeria	–	0.52	0.28	0.42
Antigua and Barbuda	0	0	0	0
Bahamas	0	0	0	0
Barbados	–	4.00	0	12.0
Belize	0	0	0	0
Bolivia	0	0	0	0
Bosnia and Herzegovina	–	0.55	0.28	–
Brazil	1.1	0.84	0.45	0.83
Chile	–	1.50	1.00	1.43

Table 6 (continued)

Country / area	*Teletherapy units*			*Brachytherapy afterloading units*
	X-ray	*Radionuclide*	*LINACs*	
China	0.19	0.45	0.24	0.26
Colombia	–	0.81	0.32	0.64
Costa Rica	0.57	0.86	0	2.00
Dominica	0	0	0	0
Dominican Republic	–	1.04	0.13	0.52
El Salvador	–	0.54	0	1.63
Grenada	0	0	0	0
Honduras	–	0.36	0	0.36
Jordan	0.19	0.38	0.58	0.19
Libyan Arab Jamahiriya	0.38	0.57	–	–
Malaysia	0.05	0.41	0.36	0.36
Mauritius	–	1.77	1.77	1.77
Mexico	0.08	0.99	0.26	0.78
Nicaragua	–	0.25	0	1.25
Oman	0	0	0	0
Pakistan	–	0.01	0.01	–
Paraguay	–	0.85	0.64	0
Peru	0.43	0.38	0.13	1.06
Philippines	0.03	0.16	0.04	0.07
Puerto Rico	–	0.52	0.52	0
Saint Kits and Nevis	0	0	0	0
Saint Lucia	0	0	0	0
Saint Vincent and the Grenadines	0	0	0	0
Trinidad and Tobago	–	1.55	0	1.55
Tunisia	0.22	0.78	0.11	1.67
Turkey	0.34	0.64	0.31	0.28
Average	0.22	0.52	0.26	0.38
Health-care level III				
Afghanistan	0	0	0	0
Congo	–	0.37	0	–
Egypt	–	0.21	0.21	0.09
Ghana	–	0.11	0	0.45
Guatemala	–	0.62	0	0.93
Guyana	–	0	0	0
Haiti	–	0.28	0	–
Jamaica	–	0.82	0	0
Madagascar	0.07	0.07	–	–
Morocco	0.04	0.34	0.04	–
Namibia	–	0.63	0	–
Nigeria	–	0.04	0	0.04
Sudan	0.04	0.12	0.04	0.12
Suriname	–	0	0	0
Zimbabwe	–	0.26	0.26	0.26
Average	0.03	0.15	0.06	0.13
Health-care level IV				
Angola	–	0.09	0	–
Cameroon	–	0.15	0	0.37
Ethiopia	–	0.02	0	0.02
Kenya	0	0.11	0	0.14
Liberia	–	0.45	0	–
Mozambique	–	0.06	0	–
Nepal	0	0.05	0	0
Senegal	–	0.12	0	–
Uganda	0.02	0.07	0	0.07
United Rep. of Tanzania	0.04	0.07	0	0.04
Average	0.02	0.07	0	0.07

Table 7
Temporal trends in average provision for medical radiology per million population
Data from UNSCEAR Surveys of Medical Radiation Usage and Exposures

Resource	*Years*	*Number per million population at health-care level*			
		I	*II*	*III*	*IV*
Physicians	1970–1974	–	–	–	–
	1980–1984	–	–	–	–
	1985–1990	2 600	550	180	53
	1991–1996	2 780	695	210	45
Physicians conducting radiological procedures	1970–1974	62	23	–	–
	1980–1984	76	64	4	–
	1985–1990	72	41	6	0.3
	1991–1996	106	76	5	0.1
Dentists	1991–1996	530	87	49	3
Medical x-ray generators	1970–1974	450	14	–	0.6
	1980–1984	380	71	16	10
	1985–1990	350	86	18	4
	1991–1996	290	60	40	4
Mammography x-ray generators	1991–1996	24	0.5	0.2	0.1
Dental x-ray generators	1970–1974	440	12	–	0.04
	1980–1984	460	77	5	–
	1985–1990	380	86	3	0.4
	1991–1996	440	56	11	0.1
Computed tomography scanners	1991–1996	17	2.4	0.4	0.1
Nuclear medicine gamma cameras	1991–1996	7.2	0.3	0.1	0.03
Nuclear medicine rectilinear scanners	1991–1996	0.9	0.3	0.1	0.01
Nuclear medicine PET scanners	1991–1996	0.2	0.002	0	0
Therapy x-ray units	1970–1974	14	0.2	–	–
	1980–1984	13	1.7	0.7	–
	1985–1990	4.8	5.0	0.1	0.1
	1991–1996	2.8	0.2	0.03	0.02
Radionuclide teletherapy units	1970–1974	3.1	0.1	0.1	–
	1980–1984	3.4	0.4	0.4	–
	1985–1990	2.6	0.4	0.2	0.09
	1991–1996	1.6	0.5	0.2	0.1
LINACs	1970–1974	1.0	–	–	–
	1980–1984	1.2	0.1	0.02	–
	1985–1990	2.0	0.1	0.09	–
	1991–1996	3.0	0.3	0.06	0
Brachytherapy afterloading units	1991–1996	1.7	0.4	0.1	0.1
Stereotactic radiosurgery units	1991–1996	0.04	0.03	0	0
Neutron therapy facilities	1991–1996	0.02	0.001	0	0
Heavy ion therapy facilities	1991–1996	0.01	0	0	0

Table 8
Annual numbers of medical radiation examinations and treatments (1991–1996)
Data from UNSCEAR Survey of Medical Radiation Usage and Exposures unless otherwise indicated

Country / area	*Diagnostic examinations (thousands)*			*Therapeutic treatments [a] (thousands)*		
	Medical x rays	*Dental x rays [b]*	*Radionuclide administrations*	*Teletherapy*	*Brachytherapy*	*Radionuclide administrations*
Health-care level I						
Argentina	–	–	396	–	–	6.85
Australia	10 000	–	212	32.5	1.13	–
Austria [H60]	–	–	–	–	–	2.30
Bahrain	115	28	–	–	–	–
Belarus	7 489	835	4.98	4.68	0.986	–
Bulgaria	5 000	–	27.7	1.57	4.73	0.258
Canada	24 933	–	1 805	47.3	1.95	8.37
Cayman Islands	–	–	0	0	0	0
China, Taiwan Province	10 446	–	135	–	–	–
Croatia	4 300	1 100	11.3	9.43	0.350	0.145
Cuba	–	–	–	22.2	–	–
Cyprus	610	7.87	4.33	0.605	0.012	0.052
Czech Republic	9 154	2 000	293	36.2	2.83	2.60
Denmark	2 600	2 400	77.5	7.85	–	2.34
Ecuador	1 959	184	10.3	1.35	0.124	0.452
Estonia [S29]	1 500	–	12.0	–	–	–
Finland	3 600	1 484	50.9	–	–	2.24
France	92 000	–	–	100	–	7.00
Germany	102 240	22 520	2 780	–	–	31.4
Greece [H60]	–	–	–	–	–	1.63
Hungary	4 891	420	158	37.7	3.20	1.08
Ireland	–	–	22.3	5.87	0.339	0.445
Israel [H60]	–	–	–	–	–	0.30
Italy	–	–	621	–	–	6.00
Japan	184 652	104 860	1 460	95.2 [c]	5.51 [c]	3.78 [c]
Kuwait	1 515	168	21.5	0.386	0.025	0.227
Lithuania	3 287	400	39.2	–	–	1.087
Luxembourg	425	191	21.2	0	0	–
Netherlands	9 000	2 700 [c]	240	34 [c]	2.3 [c]	4.3 [c]
New Zealand	–	–	29.1	6.25	0.172	0.562
Norway	3 062	–	–	–	–	1.02
Panama	803	–	9.22	0.790	0.141	–
Poland	24 760	2 840	–	–	–	–
Portugal [F11]	8 381	986	39.4	–	–	0.682
Qatar	248	–	2.56	0	0	0.024
Romania	10 197	632	68.5	10.5	3.67	1.53
Russian Federation	170 700	14 240	1 869	144	65.3	1.483
Slovakia	4 261	503	49.9	4.07	1.38	0.612
Slovenia	691	110	22.2	4.84	0.278	0.591
South Africa	5 580	–	–	–	–	–
Spain	25 059 [c]	5 515 [c]	474 [c]	45.7 [c]	2.64 [c]	8.38 [c]
Sweden	5 000	6 500	120	11.5	0.964	3.50
Switzerland	5 320	4 050	67.5	–	–	1.607
Ukraine	31 478	–	262	–	–	–
United Arab Emirates	904	36.7	17.3	0.552	0.022	0.058
United Kingdom	28 876	12 500	478	135	–	14.5
United States [I23]	250 000	–	8 202	515	30.0	–
Uruguay	–	–	–	4.78	0	–
Venezuela	–	–	–	34.3	–	–
Health-care level II						
Antigua and Barbuda [B33, B43]	17.6	–	0	0	0	0
Bahamas [B43]	–	–	–	0	0	–
Barbados	43.4	–	–	0.783	–	–
Belize	–	–	–	0	0	–
Bolivia	–	–	–	6.00	–	–
Brazil	39 083	16 667	1 000 [c]	200	5.5 [c]	5.00
Chile	–	–	–	30.0	–	–
China [Z9, Z13, Z29]	207 000 [c]	2 000	620 [c]	410 [c]	–	48 [c]
Colombia	–	–	–	54.7	–	–
Dominica	14.8	–	0	0	0	0
Dominican Republic	–	–	–	14.6	–	–

Table 8 (continued)

Country / area	*Diagnostic examinations (thousands)*			*Therapeutic treatments [a] (thousands)*		
	Medical x rays	*Dental x rays [b]*	*Radionuclide administrations*	*Teletherapy*	*Brachytherapy*	*Radionuclide administrations*
El Salvador	–	–	–	11.2	–	–
Grenada	15.0	–	0	0	0	0
Honduras	–	–	–	11.0	–	–
Iran (Islamic Republic of)	–	–	110	–	–	–
Jordan	235	16.0	8.13	1.39	–	0.701
Libyan Arab Jamahiriya	–	–	–	0.411	–	–
Malaysia	3 578	–	–	–	–	–
Mexico	28 365	106	98.0	10.3	1.99	3.53
Nicaragua	–	–	–	8.80	–	–
Oman	606	5.18	1.44	0	0	0
Pakistan	–	–	77.1	7.47	0.158	3.93
Paraguay	–	–	–	10.0	0	–
Peru	–	–	13.7	3.28	0.850	0.800
Puerto Rico	–	–	–	5.54	–	–
Saint Kitts and Nevis	7.30	–	0	0	0	0
Saint Lucia	18.7	–	0	0	0	0
Saint Vincent and the Grenadines	16.2	–	0	0	0	0
Trinidad and Tobago	–	–	–	1.96	–	–
Tunisia	–	–	7.08	1.20	0.200	0.380
Turkey	6 262	2 000	132	24.6	2.37	3.03
Health-care level III						
Afghanistan [L57]	–	–	–	0	–	–
Ghana	118	4.42	0.970	–	–	–
Guatamala	–	–	–	20.0	–	–
Haiti	–	–	–	13.0	–	–
Jamaica	–	–	–	5.00	0	–
Madagascar	151	–	–	0.904	–	–
Morocco	216	–	16.5	9.60	0.800	0.920
Sudan	956	–	2.21	1.17	0.024	0.167
Health-care level IV						
Ethiopia	–	–	0.848	–	–	0.025
United Rep. of Tanzania	831	1.90	0.666	1.42	–	0.007

a Complete courses of treatment.
b Some values may refer to number of films.
c These revised data were received by the Committee after completion of the global analysis.

The entries in this Table are qualified as follows:

Afghanistan: No radiotherapy or oncology services in country [L57].
Argentina: Totals for diagnostic and therapeutic procedures with radionuclides inferred from data for about 25% of Nuclear Medicine Centres.
Barbados: Data from reference [B43]. Total for medical x-ray examinations refers to public sector. Total for teletherapy refers to estimated annual number of new patients with cancer.
Brazil: Except for data on diagnostic radionuclide administrations and brachytherapy treatments, numbers extrapolated from data for Paraná State (with a population of 9 million and a social and economic profile above the average for Brazil). Data for diagnostic dental x-ray examinations include only intraoral procedures.
Canada: Total for diagnostic medical x-ray examinations from reference [A15]. Totals for diagnostic and therapeutic radionuclide procedures extrapolated from data for the province of Ontario (representing about 37% of population). Totals for teletherapy and brachytherapy treatments extrapolated from data for the Nova Scotia Cancer Treatment and Research Foundation, the Cross Cancer Institute (Northern Alberta) and the province of Manitoba (collectively representing about 14% of the population).
China: Data shown for teletherapy also include brachytherapy.
China (Taiwan): Data on diagnostic radionuclide procedures from reference [L6].
Cyprus: Data for medical and dental x rays extrapolated from information for 50% of poulation; data for diagnostic and therapeutic radionuclide procedures extrapolated from information for 90% of population.
Finland: Data for therapeutic radionuclide administrations from reference [K59].
France: Data on diagnostic medical x rays from reference [B40]; this total includes dental x rays. Data for therapeutic treatments represents annual number of patients undergoing radiotherapy [S50]. Data on therapeutic radionuclide administrations from reference [H60].
Ghana: Data on diagnostic medical and dental x rays from reference [S38]. Data on diagnostic radionuclide examinations from reference [A16].
Italy: Data on diagnostic medical x-rays from reference [B40]; this total includes dental x rays.
Japan: Data on diagnostic dental x-rays from reference [I30].
Mexico: Total for diagnostic medical x-ray examinations inferred from data for about 35% of radiology Institutions. Data for diagnostic dental x-ray examinations include only panoramic procedures.
Morocco: Total for brachytherapy treatments includes only gynaecological tumours.
New Zealand: Data for therapeutic radionuclide administrations from reference [L28].
Norway: Data on therapeutic radionuclide administrations from reference [H60].

Table 8 (continued)

Poland: Data on diagnostic x-rays from reference [S49].
Portugal: Data on diagnostic exminations from reference [F11]. Data on therapeutic radionuclide administrations from reference [H60].
Switzerland: Data on therapeutic radionuclide administrations from reference [H60].
Ukraine: Total for medical x-ray examinations includes dental x-ry examinations.
United Kingdom: Data for medical and dental x-ray examinations from reference [T15]. Data for diagnostic examinations with radionuclides from reference [E11]. Estimated total for 'Teletherapy' includes also brachytherapy treatments. Data for therapeutic radionuclide administrations from reference [C27].
Uruguay: Data from reference [B43]. Total for teletherapy refers to estimated annual number of new patients with cancer.

Dominica, Grenada, Saint Kitts and Nevis, Saint Lucia, Saint Vincent and the Grenadines:
Data from reference [B43]. Total for medical x-ray examinations refers to public sector.

Bolivia, Chile, Colombia, Cuba, Dominican Republic, El Salvador, Guatemala, Haiti, Honduras, Jamaica, Nicaragua, Paraguay, Puerto Rico, Trinidad and Tobago, Venezuela:
Data from reference [B43]. Total for teletherapy refers to estimated annual number of new patients with cancer.

Table 9
Global use of medical radiology (1991-1996)
Estimates derived from UNSCEAR Survey of Medical Radiation Usage and Exposures [a]

P A R T A: NORMALIZED VALUES

Quantity		*Number per million population at health-care level*				
		I	*II*	*III*	*IV*	*Globally*
Physicians						
All physicians		2 800	700	210	45	1 100
Physicians conducting radiological procedures		110	80	5	0.1	70
X-ray imaging						
Equipment	Medical	290	60	40	4	110
	Dental	440	60	10	0.1	150
	Mammography	24	0.5	0.2	0.1	7
	CT	17	2	0.4	0.1	6
Annual number of examinations	Medical [b]	920 000	150 000	20 000		330 000
	Dental [c]	310 000	14 000	200		90 000
Radionuclide imaging						
Equipment	Gamma cameras	7.2	0.3	0.1	0.03	2.1
	Rectilinear scanners	0.9	0.3	0.1	0.01	0.4
	PET scanners	0.2	0.002	0	0	0.05
Annual number of examinations [d]		19 000	1 100	280	17	5 600
Radionuclide therapy						
Annual number of patients [e]		170	40	20	0.4	65
Teletherapy						
Equipment	X-ray	2.8	0.2	0.03	0.02	0.9
	Radionuclide	1.6	0.5	0.2	0.1	0.7
	LINAC	3.0	0.3	0.06	0	0.9
Annual number of patients [f]		1 500	690	470	50	820
Brachytherapy						
Afterloading units		1.7	0.4	0.1	0.1	0.7
Annual number of patients [g]		200	17	15	(15) [h]	70

P A R T B: TOTAL VALUES

Quantity	*Total number (millions) at health-care level*				
	I	*II*	*III*	*IV*	*Globally*
Physicians					
All physicians	4.3	2.1	0.13	0.03	6.6
Physicians conducting radiological procedures	0.16	0.23	0.003	0.0001	0.4

Table 9 (continued)

Quantity		*Total number (millions) at health-care level*				
		I	*II*	*III*	*IV*	*Globally*
X-ray imaging						
Equipment	Medical	0.45	0.2	0.02	0.002	0.7
	Dental	0.67	0.2	0.01	< 0.0001	0.9
	Mammography	0.04	0.001	0.0001	0.0001	0.04
	CT	0.027	0.007	0.0003	0.0001	0.034
Annual number of examinations	Medical [b]	1 410	470	24		1 910
	Dental [c]	475	42	0.24		520
Radionuclide imaging						
Equipment	Gamma cameras	0.011	0.001	0.0001	0.00002	0.012
	Rectilinear scanners	0.001	0.001	0.0001	0.00001	0.002
	PET scanners	0.0003	0.00001	0	0	0.00031
Annual number of examinations [d]		29	3.5	0.2	0.01	32.5
Radionuclide therapy						
Annual number of patients [e]		0.3	0.1	0.01	0.0002	0.4
Teletherapy						
Equipment	X-ray	0.004	0.001	0.00002	0.00001	0.005
	Radionuclide	0.002	0.002	0.0001	0.00004	0.004
	LINAC	0.005	0.001	0.00004	0	0.005
Annual number of patients [f]		2.3	2.1	0.3	0.03	4.7
Brachytherapy						
Afterloading units		0.003	0.001	0.0001	0.00004	0.004
Annual number of patients [g]		0.3	0.05	0.01	(0.01) [h]	0.4
Population						
Total Population		1 530	3 070	640	565	5 800

a Extrapolated, with rounding, from limited samples of data.
b Estimates based on following population sample sizes for global model: 67% for level I, 50% for level II, 9% for levels III/IV, and 46% overall.
c Estimates based on following population sample sizes for global model: 39% for level I, 49% for level II, 4% for levels III/IV, and 37% overall.
d Estimates based on following population sample sizes for global model: 68% for level I, 18% for level II, 11% for level III, 16% for level IV, and 30% overall.
e Estimates based on following population sample sizes in relation to global model: 44% for level I, 16% for level II, 8% for level III, 16% for level IV, and 22% overall.
f Estimates based on following population sample sizes in relation to global model: 56% for level I, 19% for level II, 17% for level III, 5% for level IV, and 27% overall.
g Estimates based on following population sample sizes in relation to global model: 38% for level I, 11% for level II, 9% for level III, 0% for level IV, and 17% overall.
h Assumed value in the absence of survey data.

Table 10
Chronology of key technical advances in diagnostic radiology

Date	*Development*
1895	Discovery of x rays (Röntgen); first clinical image
1920s	Barium contrast studies
1930s	Intravenous contrast media
1940s	Angiography
1950s	Fluoroscopic image intensifiers; catheter techniques
1960s	Early work on rare-earth intensifying screens
1970s	Computed tomography (CT)
1980s	Magnetic resonance imaging (MRI); digital radiology
1990s	Interventional radiological techniques; picture archive and communications systems (PACS); teleradiology

Table 11
Aspects of practice that influence doses to patients from x-ray examinations
[B11, B53, C1, C3, C11, G30, G31, G32, H1, H10, H11, J2, L1, L4, L30, M42, M43, M49, N7, N8, N28, S3, S19, S20, S21, S52, S59, S64, T1, U3, V3, V13, W16, W40]

Aspect	*Influence*
Procedure-related	
Strict referral criteria	Reduce per caput doses by removing clinically unhelpful examinations
Availability of previously taken films	Promotes elimination of retakes and thus reduction of per caput doses
Number of radiographs per examination	Positively correlated with dose
Fluoroscopy time and current	Positively correlated with dose
Quality assurance programmes	Promote reductions in per caput doses
Routine patient dosimetry and reference doses	Promote reductions in per caput doses
X-ray beam collimation	Beam area positively correlated with dose
Shielding of sensitive organs	Facilitates dose reduction
Choice of projection	Organ doses can depend on beam projection
Optical density of radiographs	Positively correlated with dose
Compression of attenuating tissue	Reduces dose and scatter and improves image quality
Matching exposure factors to patient stature	May reduce doses
Equipment-related	
Exposure time	Use of long times and low currents may increase dose due to reciprocity law failure
Applied potential	Higher settings may reduce dose and contrast
X-ray tube voltage waveform	Three-phase and constant potential generators reduce dose and contrast
X-ray target material	Molybdenum may increase dose and contrast compared with tungsten
Beam filtration, thickness	Increasing thickness reduces dose and contrast
Beam filtration, material	Rare-earth K-edge filters and other materials can reduce dose and contrast
Beam filtration, shape	Dose reduction with special semitransparent filters in radiography and fluoroscopy
Anti-scatter grids	Appropriate design and use to increase image quality and dose when required
Air gap technique	May obviate need for grid
Attenuation between patient and image receptor	Low attenuation materials (e.g. carbon fibre tables) reduce dose
Screen/film combination	Dose reductions through appropriate use of faster (rare earth) screens
Film processing	Reductions in per caput doses through adherence to manufacturers instructions
Image intensifiers	Sensitive (e.g. CsI) photocathodes facilitate dose reduction
Digital image processing	May facilitate dose reduction
Fluoroscopy recording method	Video recorder reduces fluoroscopy dose compared with cine camera
Pulsed fluoroscopy with image storage device	Reduces fluoroscopy dose
Spot film photofluorography	Dose reduction with 100 mm camera compared with radiography
Picture archiving and communications systems (PACS)	Potential reductions in per caput doses from improved availability of images
Computed radiography	Potential for dose reduction from greater reliability of image reproduction
Digital imaging techniques	Potential for improved image quality, but often at expense of increased dose

Table 12
Annual numbers of examinations per 1,000 population for common types of diagnostic medical [a] x-ray procedures (1991-1996)
Data from UNSCEAR Survey of Medical Radiation Usage and Exposures unless otherwise indicated

PART A

Country / area	Chest			Limbs and joints	Spine				Pelvis and hips	Head	Abdomen	GI tract		Cholecystography	Urography	Pelvimetry
	Radiography	Photofluorography	Fluoroscopy		Lumbar	Thoracic	Cervical	All				Upper	Lower			
Health-care level I																
Australia	113	0.0003	0.57	160	28	44	15	100	37	23	15	8.1	5.8	0.85	11	0.38
Bahrain	49	– [b]	–	64	–	–	–	13	6.8	21	19	2.7	1.0	0.03	2.8	0.12
Belarus	11	435	123	84	5.8	2.0	3.9	12	4.7	12	2.8	27	3.9	0.48	3.8	–
Belgium [C26]	260	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Canada	260	–	0.38	284	–	–	–	112	25	44	22	36	15	1.0	7.8	0.04
China, Taiwan Prov.	200	–	–	–	–	–	–	112	–	29	58	51	–	12	–	–
Croatia	147	59	11	–	–	–	–	252	147	147	168	–	–	–	5.0	–
Cyprus	254	23	0	292	–	–	–	95	20	81	47	19	–	0.15	11	0
Czech Republic	145	25	5.0	229	55	38	54	150	65	87	20	12	5.2	3.7	12	–
Denmark	–	0	0	–	–	–	–	–	–	–	–	–	–	–	–	–
Ecuador	45	–	–	26	11	5.9	6.6	24	15	13	9.7	1.3	1.2	2.0	7.9	0.17
Finland	240	–	–	–	20	6.1	16	42	14	51	8.2	1.0	5.6	–	2.9	1.0
Germany	266	–	–	306	–	–	–	151	99	138	32	11	5.5	2.7	28	–
Hungary	50	24	22	126	–	–	–	33	51	90	–	12	19	0.07	2.7	–
Japan	616	17	15	172	88	14	57	159	15	63	97	118	15	6.0	14	0.91
Kuwait	323	145	0	181	35	–	31	–	19	71	63	4.7	0.77	0.11	5.7	0.29
Lithuania	79	108	69	332	–	–	–	–	–	–	92	–	–	–	–	–
Luxembourg	205	1.5	–	320	119	23	94	236	26	63	18	7.8	6.6	1.4	22	–
Netherlands	120	–	–	67	27	3.3	13	43	25	33	9.3	12	7.0	0	11	0
Norway	146	34	0.70	181	21	11	21	53	59	2.6	7.6	8.1	8.7	–	9.3	–
Panama	117	–	–	36	12	4.4	11	27	9.4	26	17	13	11	4.3	20	–
Poland [S49]	149	181	2.6	108	42	21	31	94	15	46	11	10	2.3	0	6.0	0
Qatar	235	0.04	–	–	–	–	–	30	112	26	35	2.4	1.5	0.06	7.5	0.50
Romania	54	106	112	40	10	3.6	9.2	21	14	20	15	45	10	2.7	3.0	–
Russian Federation	127	449	–	322	–	–	–	–	–	–	–	104	–	–	–	–
Slovakia	145	64	9.5	62	–	–	–	62	33	64	43	38	17	1.1	13	–
Slovenia	83	–	–	106	–	–	–	56	6.3	9.5	12	3.1	0.53	0.09	3.9	0.47
South Africa [M22]	69	–	–	–	7.3	2.2	6.1	16	8.3	–	7.7	2.9	1.5	–	3.7	–
Sweden	136	–	0.09	136	16	7.4	11	34	40	8.0	8.0	5.1	11	0.74	11	0.57
Switzerland	207	7.2	0.52	247	39	11	23	73	49	36	22	3.0	3.9	1.7	8.5	–
United Arab Emirates	111	65	0.56	79	28	2.1	2.7	33	9.2	23	26	2.9	1.1	0.19	3.3	3.8
United Kingdom	141	–	–	147	19	5.0	14	40	31	28	21	4.9	6.1	1.2	4.6	–
Average	236	202	21	212	45	12	30	100	36	60	41	54	8.6	3.1	12	0.56

Table 12 (continued)

Country / area	Chest			Limbs and joints	Spine				Pelvis and hips	Head	Abdo-men	GI tract		Chole-cysto-graphy	Uro-graphy	Pelvi-metry
	Radio-graphy	Photo-fluorography	Fluoro-scopy		Lumbar	Thoracic	Cervical	All				Upper	Lower			
Health-care level II																
Brazil	77	–	–	70	5.3	2.4	25	33	20	36	7.1	2.6	1.1	0.89	5.0	–
China [Z9, Z13]	11	–	83	11	–	–	–	4.0	–	–	12	5.4	–	–	–	–
Costa Rica	29	–	–	1.8	–	–	–	12	1.9	8.3	8.6	–	–	–	–	–
Jordan	10	–	–	5.1	–	–	–	4.4	3.2	5.7	6.8	–	0.19	0.02	0.58	–
Malaysia	115	0	0	41	–	–	–	–	–	–	15	0.34	–	0.02	0.65	–
Mexico	88	0.24	0.84	60	–	–	–	28	12	34	33	4.3	2.7	1.9	7.1	2.9
Oman	81	0	0	89	–	–	–	34	6.8	27	22	2.5	–	0.12	2.2	0
Turkey	29	1.1	0.02	15	–	–	–	14	3.7	10	6.8	0.96	0.49	0.03	1.9	0.0003
Average	24	0.50	72	20	5.3	2.4	25	8.9	14	30	13	4.8	1.5	0.94	4.7	1.7
Health-care level III																
Ghana	3.0	–	–	–	0.62	–	–	–	0.54	0.55	–	–	–	–	–	–
Madagascar	4.9	–	–	2.4	–	–	–	–	–	1.9	1.1	0.06	0.03	0.001	0.05	0.006
Sudan	6.2	–	–	8.7	2.0	0.72	0.94	3.6	2.2	6.5	2.2	1.4	2.9	0.26	2.2	0.72
Average	4.9	–	–	6.5	1.4	0.72	0.94	3.6	1.5	3.5	1.8	0.96	1.9	0.17	1.4	0.47
Health-care level IV																
United Rep. Tanzania	4.9	0	0	7.4	–	–	–	3.5	2.1	2.8	2.3	1.6	1.4	0.01	0.003	0
Average	4.9	0	0	7.4	–	–	–	3.5	2.1	2.8	2.3	1.6	1.4	0.01	0.003	0

PART B

Country / area	Mammography			CT			Angiography			Interventional procedures		Total of all medical examinations
	Screening	Clinical	All	Head	Body	All	Cerebral	Cardiac	All	PTCA	All	
Health-care level I												
Australia	–	–	27	24	28	52	0.35	4.9	6.8	–	–	565
Bahrain	–	–	1.4	3.4	2.0	5.4	–	–	0.21	–	–	202
Belarus	–	–	–	–	–	5.6	–	–	1.0	–	0.02	726
Belgium [C26]	–	–	–	–	–	–	–	–	–	0.52	–	–
Bulgaria	–	–	–	–	–	–	–	–	–	–	–	589
Canada	–	–	79	19	22	41	–	–	7.0	–	0.31	892

Table 12 (continued)

Country / area	*Mammography*			*CT*			*Angiography*			*Interventional procedures*		*Total of all medical examinations*
	Screening	*Clinical*	*All*	*Head*	*Body*	*All*	*Cerebral*	*Cardiac*	*All*	*PTCA*	*All*	
Health-care level I (continued)												
China, Taiwan Prov.	–	–	0.18	–	–	21	–	–	0.89	–	–	480
Croatia	–	–	1.7	–	–	9.7	0.13	0.21	0.80	–	–	903
Cyprus	–	–	17	–	–	69	–	5.4	6.4	0.07	0.12	937
Czech Republic	0	12	12	22	11	34	0.45	1.1	5.6	–	31	883
Denmark	–	–	–	–	–	–	–	–	–	–	–	510
Ecuador	–	–	1.1	–	–	3.5	–	–	0.16	–	0.09	151
Estonia [S29]	–	–	–	–	–	–	–	–	–	–	–	1 000
Finland	27	6.4	34	15	9.4	25	–	0.96	–	0.20	1.7	704
France [B40]	–	–	–	–	–	33	–	–	–	–	–	–
Germany	–	–	68	20	44	64	–	–	24	1.1	2.2	1 254
Greece [P12]	–	–	–	25	61	87	–	–	–	–	–	–
Hungary	–	–	2.1	26	17	43	0.13	–	1.2	0.08	0.30	475
Israel [S48]	–	–	–	–	–	78	–	–	–	–	–	–
Italy [B40]	–	–	–	–	–	29	–	–	–	–	–	–
Japan	–	5.2	–	–	–	–	1.1	1.2	5.6	–	–	1 477
Kuwait	0	2.0	2.0	7.5	4.2	12	0.06	–	1.0	–	2.1	896
Lithuania	–	4.8	–	–	–	–	–	–	4.2	–	–	886
Luxembourg	17	33	50	31	45	76	0.99	–	13	–	–	1 046
Netherlands	35 [c]	12	47 [c]	13	19	32	–	–	0.63	0.80	1.3	600
Norway	–	43	–	21	27	48	–	–	11	–	–	708
Panama	–	–	8.8	6.4	3.8	10	0.22	0.52	0.90	–	–	300
Poland [S49]	–	–	7.3	3.0	1.4	4.4	0.20	0.80	2.8	–	0.80	641
Portugal [F11]	–	–	20	–	–	30	–	–	–	–	–	850
Qatar	–	–	0.72	–	–	8.3	–	–	0.21	–	0.58	459
Romania	–	–	1.8	–	–	0.02	–	–	0.63	–	–	450
Russian Federation	–	–	4.6	–	–	–		–	–	–	–	1 151
Slovakia	3.5	7.0	11	20	34	54	2.0	0.69	5.6	0.38	1.0	800
Slovenia	–	–	14	–	–	25	–	–	3.7	–	1.3	348
South Africa [M22]	–	–	–	–	1.9	–	–	–	1.2	–	–	180
Spain	–	–	–	–	–	15	–	1.5	2.0	0.32	0.6	–
Sweden	63	17	80	20	18	39	0.51	4.2	8.1	0.68	3.0	568
Switzerland	–	–	29	16	26	43	1.4	4.4	11	1.2	4.7	750
Ukraine [K18]	–	–	–	1.0	1.8	2.8	–	–	–	–	–	600
United Arab Emirates	0.79	0.52	1.3	9.2	2.7	12	0.09	0.02	0.45	–	0.13	378
United Kingdom	21	5.6	27	9.5	12	21	0.21	2.8	5.2	–	4.5	489
United States	–	–	–	–	–	91	–	–	–	–	–	962
Average	21	7.1	25	14	19	48	0.68	1.8	6.8	0.75	2.7	920

Table 12 (continued)

Country / area	*Mammography*			*CT*			*Angiography*			*Interventional procedures*		*Total of all medical examinations*
	Screening	*Clinical*	*All*	*Head*	*Body*	*All*	*Cerebral*	*Cardiac*	*All*	*PTCA*	*All*	
Health-care level II												
Antigua and Barbuda	–	–	–	–	–	–	–	–	–	–	–	271
Barbados	–	–	–	–	–	–	–	–	–	–	–	174
Brazil	–	–	3.3	–	–	4.8	–	–	0.33	–	–	261
China [Z9, Z13]	–	–	–	–	–	10.3 [c]	–	–	–	–	–	173 [c]
Dominica	–	–	–	–	–	–	–	–	–	–	–	185
Grenada	–	–	–	–	–	–	–	–	–	–	–	158
Jordan	0	0.25	0.25	1.0	0.86	1.9	–	–	–	–	–	45
Malaysia	0	1.3	1.3	0.79	0.58	1.4	0.05	0.24	–	–	–	183
Mexico	1.1	1.8	2.9	4.2	2.8	7.0	–	–	0.68	–	1.3	306
Oman	–	–	0.49	–	–	2.0	0.10	0.42	0.52	–	0.003	269
Saint Kitts and Nevis	–	–	–	–	–	–	–	–	–	–	–	203
Saint Lucia	–	–	–	–	–	–	–	–	–	–	–	134
Saint Vincent and the Grenadines	–	–	–	–	–	–	–	–	–	–	–	147
Turkey	–	–	1.5	–	–	13	–	–	0.54	–	0.45	98
Average	0.85	1.7	2.7	3.5	2.3	6.7	0.06	0.25	0.48	–	0.94	154
Health-care level III												
Ghana	–	–	0.011	–	–	0.08	–	–	–	–	–	7
Madagascar	–	–	0.003	–	–	0.09	–	–	0	–	0	11
Morocco	–	–	–	–	–	–	–	–	–	–	–	8
Sudan	–	–	–	–	–	–	–	–	–	–	–	37
Average	–	–	0.01	–	–	0.08	–	–	0	–	0	17
Health-care level IV												
United Rep. Tanzania	–	–	–	–	–	0.21	–	–	0	–	0	29
Average	–	–	–	–	–	0.21	–	–	0	–	0	29

a Excluding dental x-ray examinations.
b No data available.
c These revised data were received by the Committee after completion of the global analysis.

The entries in this Table are qualified as follows:

Brazil: Survey data for Paraná State (with a population of 9 million and a social and economic profile above the average for Brazil).
Canada: Data for total of all medical x-ray examinations from reference [A15]; data for specific examinations on the basis of information (excluding procedures in private clinics) for the province of Ontario (representing about 37% of population).
China: Data for 'GI tract' include both 'Upper' and 'Lower' categories.

Table 12 (continued)

China, Taiwan Province: Data for 'Chest radiography' include all chest examinations. Data for 'GI tract' include both 'Upper' and 'Lower' categories.
Costa Rica: Data from Hospital Calderón Guardia (serving one third of the population).
Cyprus Survey data relating to 50% of population.
Ghana: Data from reference [S38]. Data for 'Pelvis/hip' include 'Abdomen' examinations.
Lithuania: Data from Vilnius University Hospital.
Madagascar: Data for 'Head' include examinations of the spine.
Malaysia: Data for 'Limbs and joints' include 'Head' examinations. Data for 'GI tract' include both 'Upper' and 'Lower' categories.
Mexico: Data for 'Head' include examinations of the neck.
Oman: Data for 'GI tract' include both 'Upper' and 'Lower' categories.
Romania: Data from all counties except Bucharest.
Russian Federation: Data for 'Limbs and joints' include all examinations of the skeleton. Data for 'GI tract' include all examinations of digestive organs.
Slovakia: Survey data relating to population base of about 2 million.
Slovenia: Survey data relating to population base of about 1.8 million.
Spain: Data for CT from reference [B40]; data for angiography and interventional procedures from reference [V8].
Sweden: Survey data from a sample of health districts covering about one−quarter of the population.
Turkey: On the basis of data from Hacettepe University Hospital.
United Arab Emirates: 1% of pelvimetry examinations conducted using CT/digital techniques.
United Kingdom: Data from reference [T15]. Data for 'Chest radiography' include all chest examinations.
United States: Data for CT from reference [B40]. Data for total of all medical examinations from [I23].

Antigua, Barbados, Dominica,, Grenada, Saint Kitts and Nevis, Saint Lucia, Saint Vincent and the Grenadines: Data for public sector from [B43].

Table 13
Percentage contributions by types of procedure to annual total numbers of diagnostic medical [a] x-ray examinations (1991–1996)
Based on data and qualifications from Table 12

PART A

Country / area	Chest			Limbs and joints	Spine				Pelvis and hips	Head	Abdomen	GI tract		Cholecystography	Urography	Pelvimetry
	Radiography	Photofluorography	Fluoroscopy		Lumbar	Thoracic	Cervical	All				Upper	Lower			
Health-care level I																
Australia	20	0.0001	0.1	28	5.0	7.7	2.6	18	6.6	4.0	2.7	1.4	1.0	0.2	2.0	0.07
Bahrain	24	–	–	31	–	–	–	6.7	3.4	10	9.3	1.3	0.5	0.01	1.4	0.06
Belarus	1.5	60	17	12	0.8	0.3	0.5	1.6	0.7	1.7	0.4	3.7	0.5	0.07	0.5	–
Canada	29	–	0.04	32	–	–	–	13	2.8	4.9	2.4	4.1	1.7	0.1	0.9	0.004
China, Taiwan Prov.	42	–	–	–	–	–	–	23	–	6.1	12	11	–	2.6	–	–
Croatia	16	6.5	1.2	–	–	–	–	28	16	16	19	–	–	–	0.6	–
Cyprus	27	2.4	0	31	–	–	–	10	2.1	8.7	5.1	2.0	–	0.02	1.2	0
Czech Republic	16	2.8	0.6	26	6.2	4.3	6.1	17	7.4	9.9	2.3	1.4	0.6	0.4	1.4	–
Denmark	–	0	0	–	–	–	–	–	–	–	–	–	–	–	–	–
Ecuador	30	–	–	17	7.3	3.9	4.4	16	9.9	8.8	6.4	0.9	0.8	1.3	5.3	0.1
Finland	34	–	–	–	2.9	0.9	2.2	6.0	1.9	7.2	1.2	0.2	0.8	–	0.4	0.1
Germany	21	–	–	24	–	–	–	12	7.9	11	2.5	0.8	0.4	0.2	2.2	–
Hungary	10	5.0	4.6	27	–	–	–	6.9	11	19	–	2.6	4.0	0.02	0.6	–
Japan	42	1.2	1.0	12	6.0	0.9	3.9	11	1.0	4.3	6.5	8.0	1.0	0.4	0.9	0.06
Kuwait	36	16	0	20	3.9	–	3.5	–	2.1	7.9	7.0	0.5	0.1	0.01	0.6	0.03
Lithuania	8.9	12	7.8	37	–	–	–	–	–	–	10	–	–	–	–	–
Luxembourg	20	0.14	–	31	11	2.2	9.0	23	2.5	6.0	1.7	0.8	0.6	0.1	2.1	–
Netherlands	20	–	–	11	4.5	0.6	2.2	7.2	4.2	5.5	1.6	2.0	1.2	0	1.8	0
Norway	21	4.8	0.1	26	3.0	1.5	3.0	7.5	8.3	0.4	1.1	1.1	1.2	–	1.3	–
Panama	39	–	–	12	4.1	1.5	3.6	9.1	3.1	8.6	5.6	4.3	3.6	1.4	6.6	–
Poland	23	28	0.4	17	6.6	3.2	4.8	15	2.3	7.1	1.7	1.6	0.4	0	0.9	0
Qatar	51	0.01	–	–	–	–	–	6.5	24	5.6	7.6	0.5	0.3	0.01	1.6	0.1
Romania	12	23	25	9.0	2..3	0.8	2.0	4.6	3.2	4.5	3.3	10	2.3	0.6	0.7	–
Russian Federation	11	39	–	28	–	–	–	–	–	–	–	9.0	–	–	–	–
Slovakia	18	7.9	1.2	7.7	–	–	–	7.7	4.2	8.0	5.4	4.8	2.1	0.1	1.6	–
Slovenia	24	–	–	30	–	–	–	16	1.8	2.7	3.4	0.9	0.2	0.03	1.1	0.1
South Africa	38	–	–	–	4.1	1.2	3.4	8.7	4.6	–	4.3	1.6	0.8	–	2.1	–
Sweden	24	–	0.02	24	2.8	1.3	1.9	6.0	7.0	1.4	1.4	0.9	2.0	0.1	2.0	0.1
Switzerland	28	1.0	0.07	33	5.2	1.5	3.0	9.7	6.6	4.8	2.9	0.4	0.5	0.2	1.1	–
United Arab Emirates	29	17	0.2	21	7.3	0.6	0.7	8.6	2.4	6.1	6.9	0.8	0.3	0.1	0.9	1.0
United Kingdom	29	–	–	30	3.9	1.0	2.9	8.1	6.3	5.8	4.2	1.0	1.2	0.2	0.9	–
Average [b]	25	19	2.1	21	5.2	1.5	3.6	11	4.0	6.5	4.6	5.7	1.0	0.3	1.3	0.1

Table 13 (continued)

Country / area	Chest			Limbs and joints	Spine				Pelvis and hips	Head	Abdo-men	GI tract		Chole-cysto-graphy	Uro-graphy	Pelvi-metry
	Radio-graphy	Photo-fluorography	Fluoro-scopy		Lumbar	Thoracic	Cervical	All				Upper	Lower			
Health-care level II																
Brazil	29	–	–	27	2.1	0.9	9.7	13	7.6	14	2.7	1.0	0.4	0.3	1.9	–
China	8.1	–	63	8.1	–	–	–	3.0	–	–	9.1	4.1	–	–	–	–
Costa Rica	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Jordan	22	–	–	11	–	–	–	9.7	7.2	13	15	–	0.4	0.04	1.3	–
Malaysia	63	0	0	22	–	–	–	–	–	–	8.3	0.2	–	0.01	0.4	–
Mexico	29	0.08	0.3	20	–	–	–	9.2	3.9	11	11	1.4	0.9	0.6	2.3	0.9
Oman	30	0	0	33	–	–	–	13	2.5	10	8.2	0.9	–	0.05	0.8	0
Turkey	29	1.1	0.02	15	–	–	–	14	3.8	10	6.9	1.0	0.5	0.03	2.0	0.0003
Average [b]	16	0.2	50	13	2.1	0.9	9.7	5.8	5.9	13	8.2	3.0	0.6	0.4	2.0	0.8
Health-care level III																
Ghana	45	–	–	–	9.3	–	–	–	8.1	8.3	–	–	–	–	–	–
Madagascar	46	–	–	22	–	–	–	–	–	17	11	0.6	0.2	0.01	0.5	0.05
Sudan	17	–	–	24	5.3	2.0	2.6	9.8	5.9	18	5.9	3.9	7.8	0.7	5.9	2.0
Average [b]	23	–	–	23	5.7	2.0	2.6	9.8	6.1	17	6.5	3.5	6.8	0.6	5.2	1.7
Health-care level IV																
United Rep. Tanzania	17	–	–	25	–	–	–	12	7.2	9.6	7.8	5.4	4.8	0.02	0.01	0
Average [b]	17	–	–	25	–	–	–	12	7.2	9.6	7.8	5.4	4.8	0.02	0.01	0

PART B

Country / area	Mammography			CT			Angiography			Interventional procedures		Total of all medical examinations
	Screening	Clinical	All	Head	Body	All	Cerebral	Cardiac	All	PTCA	All	
Health-care level I												
Australia	–	–	4.7	4.2	5.0	9.2	0.06	0.9	1.2	–	–	100
Bahrain	–	–	0.7	1.7	1.0	2.7	–	–	0.1	–	–	100
Belarus	–	–	–	–	–	0.8	–	–	0.1	–	0.003	100
Canada	–	–	8.9	2.1	2.5	4.6	–	–	0.8	–	0.04	100
China, Taiwan Prov.	–	–	0.04	–	–	4.3	–	–	0.2	–	–	100
Croatia	–	–	0.2	–	–	1.1	0.01	0.02	0.1	–	–	100

Table 13 (continued)

Country / area	*Mammography*			*CT*			*Angiography*			*Interventional procedures*		*Total of all medical examinations*
	Screening	*Clinical*	*All*	*Head*	*Body*	*All*	*Cerebral*	*Cardiac*	*All*	*PTCA*	*All*	
Health–care level I (continued)												
Cyprus	–	–	1.8	–	–	7.3	–	0.6	0.7	0.01	0.01	100
Czech Republic	0	1.3	1.3	2.5	1.3	3.8	0.05	0.1	0.6	–	3.5	100
Ecuador	–	–	0.8	–	–	2.3	–	–	0.1	–	0.06	100
Finland	3.9	0.9	4.8	2.2	1.3	3.5	–	0.1	–	0.03	0.2	100
Germany	–	–	5.4	1.6	3.5	5.1	–	–	1.9	0.09	0.2	100
Hungary	–	–	0.4	5.5	3.5	9.0	0.03	–	0.3	0.02	0.06	100
Japan	–	0.4	–	–	–	–	0.08	0.08	0.4	–	–	100
Kuwait	0	0.2	0.2	0.8	0.5	1.3	0.01	–	0.1	–	0.2	100
Lithuania	–	0.5	–	–	–	–	–	–	0.5	–	–	100
Luxembourg	1.6	3.2	4.8	3.0	4.3	7.3	0.09	–	1.2	–	–	100
Netherlands	5.8[c]	2.0	7.8 [c]	2.1	3.2	5.3	–	–	0.1	0.1	0.2	100
Norway	–	6.1	–	2.9	3.8	6.7	–	–	1.5	–	–	100
Panama	–	–	2.9	2.1	1.3	3.4	0.07	0.2	0.4	–	–	100
Poland	–	–	1.1	0.5	0.2	0.7	0.03	0.1	0.4	–	0.1	100
Portugal	–	–	2.4	–	–	3.5	–	–	–	–	–	100
Qatar	–	–	0.2	–	–	1.8	–	–	0.05	–	0.1	100
Romania	–	–	0.4	–	–	0.004	–	–	0.1	–	–	100
Russian Federation	–	–	0.4	–	–	–	–	–	–	–	–	100
Slovakia	0.4	0.9	1.3	2.5	4.2	6.8	0.3	0.1	0.7	0.05	0.1	100
Slovenia	–	–	4.0	–	–	7.3	–	–	1.1	–	0.4	100
South Africa	–	–	–	–	1.1	–	–	–	0.7	–	–	100
Sweden	11	3.0	14	3.6	3.2	6.8	0.09	0.7	1.4	0.1	0.5	100
Switzerland	–	–	3.8	2.2	3.5	5.7	0.2	0.6	1.4	0.2	0.6	100
Ukraine	–	–	–	0.2	0.3	0.5	–	–	–	–	–	100
United Arab Emirates	0.2	0.1	0.3	2.4	0.7	3.1	0.02	0.01	0.1	–	0.03	100
United Kingdom	4.4	1.1	5.5	1.9	2.4	4.4	0.04	0.6	1.1	–	0.9	100
United States	–	–	–	–	–	9.5	–	–	–	–	–	100
Average [b]	3.7	0.7	2.9	1.7	2.5	6.4	0.1	0.2	0.8	0.1	0.4	100
Health-care level II												
Brazil	–	–	1.3	–	–	1.8	–	–	0.1	–	–	100
Jordan	0	0.5	0.5	2.2	1.9	4.1	–	–	–	–	–	100
Malaysia	0	0.7	0.7	0.4	0.3	0.8	0.03	0.1	–	–	–	100
Mexico	0.4	0.6	1.0	1.4	0.9	2.3	–	–	0.2	–	0.4	100
Oman	–	–	0.2	–	–	0.8	0.04	0.2	0.2	–	0.001	100
Turkey	–	–	1.6	–	–	13	–	–	0.6	–	0.5	100
Average [b]	0.3	0.6	1.2	1.3	0.8	2.9	0.03	0.1	0.2	–	0.4	100

Table 13 (continued)

Country / area	*Mammography*			*CT*			*Angiography*			*Interventional procedures*		*Total of all medical examinations*
	Screening	*Clinical*	*All*	*Head*	*Body*	*All*	*Cerebral*	*Cardiac*	*All*	*PTCA*	*All*	
Health-care level III												
Ghana	–	–	0.2	–	–	1.2	–	–	–	–	–	100
Madagascar	–	–	0.02	–	–	0.8	–	–	0	–	0	100
Average [b]	–	–	0.1	–	–	1.0	–	–	0	–	0	100
Health-care level IV												
United Rep. Tanzania	–	–	–	–	–	0.7	–	–	0	–	0	100
Average [b]	–	–	–	–	–	0.7	–	–	0	–	0	100

a Excluding dental x-ray examinations.
b Overall averages for sample calculated as total number of each particular type of examination divided by total number of all examinations.
c These revised data were received by the Committee after completion of the global analysis.

Table 14
Distribution by age and sex of patients undergoing types of diagnostic x-ray examination (1991–1996)
Data from UNSCEAR Survey of Medical Radiation Usage and Exposures unless otherwise indicated

Health-care level	*Country / area*	*Age distribution (%)*			*Sex distribution (%)*	
		0–15 years	*16–40 years*	*>40 years*	*Male*	*Female*
Chest radiography						
I	Australia	9	18	73	49	51
	Bahrain	21	33	46	59	41
	China, Taiwan Province	6	27	67	58	42
	Croatia	0	30	70	55	45
	Czech Republic	10	18	72	50	50
	Ecuador	31	34	35	53	47
	Japan	7	21	72	56	44
	Kuwait	19	53	28	62	38
	New Zealand	10	18	72	58	42
	Norway	15	14	71	54	46
	Panama	17	22	61	46	54
	Poland	9	24	67	54	46
	Romania	22	31	47	64	36
	Slovakia	14	33	53	47	53
	South Africa [M22]	20	40	40	54	46
	Sweden	7	14	79	55	45
	Switzerland	5	15	80	52	48
	United Arab Emirates	15	70	15	60	40
	Average	8	22	70	56	44
II	Brazil	– [a]	–	–	44	56
	Costa Rica	4	31	65	47	53
	Mexico	23	37	40	52	48
	Turkey	22	40	38	59	41
	Average	23	37	40	48	52
III	Sudan	22	58	20	39	61
IV	United Republic of Tanzania	15	65	20	50	50
Chest photofluorography						
I	Australia	–	–	–	50	50
	Croatia	0	35	65	55	45
	Kuwait	0	73	27	62	38
	Poland	0	60	40	59	41
	Romania	3	58	39	56	44
	Russian Federation	22	31	47	64	36
	Slovakia	11	43	46	48	52
	United Arab Emirates	0	80	20	55	45
	Average	19	35	46	63	37
II	Mexico	29	47	24	51	49
	Turkey	0	80	20	78	22
	Average	7	72	21	71	29
Chest fluoroscopy						
I	Australia	20	23	57	40	60
	Croatia	0	40	60	50	50
	Japan	1	33	66	66	34
	Poland	0	61	39	68	32
	Romania	11	38	51	55	45
	Slovakia	8	50	42	56	44
	Average	7	36	57	60	40
II	Mexico	15	43	42	50	50
	Turkey	10	63	27	69	31
	Average	15	43	42	50	50

Table 14 (continued)

Health-care level	*Country / area*	*Age distribution (%)*			*Sex distribution (%)*	
		0–15 years	*16–40 years*	*>40 years*	*Male*	*Female*
Limbs and joints						
I	Australia	16	33	51	52	48
	Bahrain	31	45	24	67	33
	Czech Republic	18	31	51	48	52
	Ecuador	32	42	26	61	39
	Japan	16	28	56	49	51
	Kuwait	22	58	20	63	37
	New Zealand	21	46	33	57	43
	Panama	22	28	50	55	45
	Poland	16	35	49	55	45
	Romania	24	36	40	60	40
	Slovakia	22	35	43	53	47
	Sweden	15	30	55	45	55
	Switzerland	15	31	54	50	50
	United Arab Emirates	20	50	30	60	40
	Average	17	30	53	50	50
II	Costa Rica	0	5	95	24	76
	Mexico	21	44	35	56	44
	Turkey	18	45	37	59	41
	Average	21	44	35	56	44
III	Sudan	8	25	67	67	33
IV	United Republic of Tanzania	10	50	40	50	50
Lumbar spine						
I	Australia	3	27	70	44	56
	Czech Republic	6	28	66	43	57
	Japan	3	21	76	51	49
	Kuwait	9	65	26	59	41
	New Zealand	6	36	58	49	51
	Norway	1	38	61	44	56
	Panama	9	25	66	44	56
	Poland	2	26	72	47	53
	Romania	5	34	61	49	51
	Slovakia	17	37	46	52	48
	South Africa [M22]	4	53	43	51	49
	Sweden	4	26	70	45	55
	Switzerland	2	29	69	47	53
	Average	3	23	74	50	50
III	Sudan	19	37	44	74	26
Thoracic spine						
I	Australia	6	27	67	36	64
	Czech Republic	10	35	55	44	56
	Ecuador	8	59	33	58	42
	Japan	9	25	66	57	43
	New Zealand	8	36	56	45	55
	Norway	3	40	57	42	58
	Panama	9	29	62	45	55
	Poland	11	31	58	48	52
	Romania	8	31	61	53	47
	Slovakia	17	39	44	52	48
	South Africa [M22]	8	56	36	47	53
	Sweden	4	19	77	45	55
	Switzerland	6	36	58	43	57
	Average	9	29	62	49	51
III	Sudan	20	30	50	60	40
Cervical spine						
I	Australia	4	28	68	38	62
	Czech Republic	6	30	64	37	63

Table 14 (continued)

Health-care level	*Country / area*	*Age distribution (%)*			*Sex distribution (%)*	
		0–15 years	*16–40 years*	*>40 years*	*Male*	*Female*
I	Japan	3	29	68	51	49
	Kuwait	13	60	29	60	40
	New Zealand	9	53	38	57	43
	Norway	2	39	59	43	57
	Panama	8	27	65	44	56
	Poland	1	25	74	41	59
	Romania	5	34	61	48	52
	Slovakia	21	37	42	50	50
	South Africa [M22]	7	58	35	53	47
	Sweden	3	24	73	45	55
	Switzerland	4	32	64	42	58
	Average	3	30	67	48	52
III	Sudan	16	46	38	62	38
Spine (general)						
I	Australia	5	29	66	40	60
	Bahrain	8	56	36	59	41
	China, Taiwan Province	7	31	62	53	47
	Croatia	13	25	63	40	60
	Poland	4	27	69	45	55
	Switzerland	3	31	66	45	55
	United Arab Emirates	0	60	40	55	45
	Average	6	29	65	46	54
II	Costa Rica	6	49	45	43	57
	Mexico	9	48	43	55	45
	Turkey	9	42	49	61	39
	Average	9	46	45	56	44
III	Sudan	18	38	44	68	32
IV	United Republic of Tanzania	5	20	75	50	50
Pelvis and hip						
I	Australia	8	16	76	37	63
	Bahrain	28	35	38	58	42
	Croatia	2	38	60	30	70
	Czech Republic	20	15	65	35	65
	Ecuador	33	47	20	40	60
	Japan	7	30	63	50	50
	Kuwait	20	54	26	61	39
	New Zealand	8	49	43	42	58
	Norway	3	14	83	29	71
	Panama	21	19	60	52	48
	Poland	25	17	58	43	57
	Romania	19	26	55	48	52
	Slovakia	34	27	39	50	50
	South Africa [M22]	8	44	48	47	53
	Sweden	7	7	86	35	65
	Switzerland	5	16	79	45	55
	United Arab Emirates	5	70	25	53	47
	Average	12	25	63	42	58
II	Costa Rica	13	30	57	19	81
	Mexico	22	42	36	37	63
	Turkey	23	39	38	53	47
	Average	22	41	37	40	60
III	Sudan	20	20	60	50	50
IV	United Republic of Tanzania	5	40	55	40	60

Table 14 (continued)

Health-care level	*Country / area*	*Age distribution (%)*			*Sex distribution (%)*	
		0–15 years	*16–40 years*	*>40 years*	*Male*	*Female*
Head						
I	Australia	27	41	32	45	55
	Bahrain	36	47	17	62	38
	China, Taiwan Province	10	37	53	57	43
	Czech Republic	24	36	40	48	52
	Ecuador	45	35	20	62	38
	Japan	24	30	46	55	45
	Kuwait	30	53	17	63	37
	New Zealand	29	48	23	62	38
	Panama	26	40	34	47	53
	Poland	16	43	41	51	49
	Romania	14	45	41	48	52
	Slovakia	20	49	31	49	51
	Sweden	30	9	61	45	55
	Switzerland	21	40	39	54	46
	United Arab Emirates	15	60	25	65	35
	Average	22	34	44	53	47
II	Costa Rica	22	51	27	47	53
	Mexico	30	42	28	55	45
	Turkey	20	39	41	62	38
	Average	28	42	30	56	44
III	Sudan	11	67	22	67	33
IV	United Republic of Tanzania	10	50	40	50	50
Abdomen						
I	Australia	13	22	65	45	55
	Bahrain	15	53	32	65	35
	China, Taiwan Province	6	26	68	55	45
	Croatia	6	35	59	50	50
	Czech Republic	5	20	75	49	51
	Ecuador	28	44	28	55	45
	Japan	5	18	77	55	45
	Kuwait	12	61	27	63	37
	New Zealand	15	65	20	51	49
	Norway	10	24	66	48	52
	Panama	21	25	54	47	53
	Poland	7	26	67	53	47
	Romania	8	39	53	51	49
	Slovakia	11	38	51	48	52
	South Africa [M22]	15	48	37	53	47
	Sweden	14	16	70	45	55
	Switzeland	7	22	71	48	52
	United Arab Emirates	18	57	25	70	30
	Average	6	22	72	54	46
II	Brazil	–	–	–	28	72
	Costa Rica	5	56	39	50	50
	Mexico	22	45	33	48	52
	Turkey	21	42	47	62	38
	Average	21	44	35	45	55
III	Sudan	33	37	30	40	60
IV	United Republic of Tanzania	10	35	55	35	65
Upper gastrointestinal tract						
I	Australia	6	25	69	45	55
	Bahrain	12	43	45	47	53
	China, Taiwan Province	3	65	32	82	18
	Croatia	0	33	67	50	50
	Czech Republic	3	25	72	43	57

Table 14 (continued)

Health-care level	*Country / area*	*Age distribution (%)*			*Sex distribution (%)*	
		0–15 years	*16–40 years*	*>40 years*	*Male*	*Female*
I	Ecuador	5	35	60	58	42
	Japan	1	22	77	62	38
	Kuwait	15	50	35	59	41
	New Zealand	31	7	62	60	40
	Norway	2	20	78	35	65
	Panama	11	25	64	43	57
	Poland	2	25	73	51	49
	Romania	4	31	65	55	45
	Slovakia	4	46	50	57	43
	South Africa [M22]	9	39	52	48	52
	Sweden	11	18	71	45	55
	Switzerland	4	12	84	43	57
	United Arab Emirates	8	60	32	55	45
	Average	1	26	73	62	38
II	Mexico	11	51	38	53	47
	Turkey	6	57	37	57	43
	Average	10	52	38	54	46
III	Sudan	20	33	47	60	40
IV	United Republic of Tanzania	10	15	75	50	50
Lower gastrointestinal tract						
I	Australia	1	3	86	42	58
	Bahrain	18	33	49	55	45
	Croatia	0	22	78	50	50
	Czech Republic	2	16	82	41	59
	Ecuador	5	35	60	58	42
	Japan	1	22	77	54	46
	Kuwait	11	49	40	51	49
	New Zealand	4	9	87	49	51
	Norway	1	21	78	35	65
	Panama	5	18	77	45	55
	Poland	1	6	93	50	50
	Romania	4	33	63	54	46
	Slovakia	6	49	45	52	48
	South Africa [M22]	3	34	63	33	67
	Sweden	3	17	80	40	60
	Switzerland	2	13	85	42	58
	United Arab Emirates	12	58	30	59	41
	Average	2	23	75	52	48
II	Mexico	6	52	42	42	58
	Turkey	3	43	54	57	43
	Average	6	51	43	44	56
III	Sudan	20	30	50	70	30
IV	United Republic of Tanzania	5	15	80	50	50
Cholecystography						
I	Australia	0	17	83	30	70
	China, Taiwan Province	2	23	75	56	44
	Croatia	0	20	80	80	20
	Czech Republic	0	11	89	36	64
	Ecuador	0	55	45	39	61
	Japan	0	17	83	51	49
	Kuwait	0	55	45	55	45
	Panama	6	32	62	44	56
	Romania	2	38	60	24	76
	Slovakia	2	42	56	51	49
	Sweden	0	25	75	40	60
	Switzerland	0	13	87	37	63
	Average	1	20	79	49	51

Table 14 (continued)

Health-care level	*Country / area*	*Age distribution (%)*			*Sex distribution (%)*	
		0–15 years	*16–40 years*	*>40 years*	*Male*	*Female*
II	Mexico	1	51	48	31	69
	Turkey	0	39	61	35	65
	Average	1	51	48	31	69
III	Sudan	0	73	27	44	56
IV	United Republic of Tanzania	10	25	65	–	–
Urography						
I	Australia	10	23	67	55	45
	Bahrain	4	59	37	66	34
	Croatia	0	20	80	100	0
	Czech Republic	11	18	71	55	45
	Ecuador	2	70	28	57	43
	Japan	3	21	76	58	42
	Kuwait	5	63	32	64	36
	New Zealand	22	30	48	55	45
	Norway	3	26	71	51	49
	Panama	10	29	61	59	41
	Poland	13	23	64	52	48
	Romania	7	33	60	55	45
	Slovakia	14	38	48	58	42
	South Africa [M22]	9	47	44	54	46
	Sweden	6	29	65	45	55
	Switzerland	16	25	59	51	49
	United Arab Emirates	5	65	30	70	30
	Average	6	25	69	57	43
II	Mexico	7	48	45	54	46
	Turkey	10	48	42	54	46
	Average	7	48	45	54	46
III	Sudan	13	60	27	50	50
IV	United Republic of Tanzania	0	10	90	75	25
Mammography (screening)						
I	Slovakia	0	32	68	0	100
	Sweden	0	0	100	0	100
	United Arab Emirates	0	0	100	0	100
	Average	0	1	99	0	100
II	Mexico	2	27	71	5	95
	Average	2	27	71	5	95
Mammography (clinical)						
I	Czech Republic	0	37	63	1	99
	Japan	0	29	71	0	100
	Kuwait	0	68	32	1	99
	New Zealand	0	14	86	0	100
	Norway	0	17	83	0	100
	Sweden	0	15	85	0	100
	United Arab Emirates	0	0	100	0	100
	Average	0	26	74	0.1	99.9
II	Mexico	0	37	63	3	97
Mammography (general)						
I	Australia	0	27	73	0	100
	Bahrain	0	33	66	1	99
	China, Taiwan Province	1	40	59	1	99

Table 14 (continued)

Health-care level	*Country / area*	*Age distribution (%)*			*Sex distribution (%)*	
		0–15 years	*16–40 years*	*>40 years*	*Male*	*Female*
I	Croatia	0	30	70	0	100
	Ecuador	0	28	72	0	100
	Kuwait	0	68	32	1	99
	Panama	0	28	72	2	98
	Poland	0	21	79	0	100
	Romania	1	43	56	1	99
	Switzerland	0.1	9	91	0.2	99.9
	United Arab Emirates	0	4	96	0	100
	Average	0.1	23	77	0.1	99.9
II	Mexico	1	33	66	4	96
	Turkey	0	38	62	1	99
	Average	1	34	65	3	97
Computed tomography (head)						
I	Australia	6	30	64	44	56
	Bahrain	23	36	42	56	44
	Czech Republic	8	23	69	47	53
	Kuwait	17	39	44	60	40
	New Zealand	10	26	64	53	47
	Panama	17	25	58	51	49
	Poland	13	20	67	50	50
	Slovakia	3	42	55	48	52
	Sweden	5	19	76	50	50
	Switzerland	4	23	73	51	49
	United Arab Emirates	15	50	35	60	40
	Average	7	27	67	48	52
II	Mexico	9	40	51	48	52
Computed tomography (body)						
I	Australia	1	21	78	48	52
	Bahrain	7	40	53	53	47
	Czech Republic	5	15	80	49	51
	Kuwait	6	43	51	56	44
	New Zealand	4	26	70	52	48
	Panama	5	29	66	50	50
	Poland	8	23	69	55	45
	Slovakia	4	44	52	51	49
	South Africa [M22]	5	46	49	52	48
	Sweden	3	20	77	55	45
	Switzerland	2	17	81	54	46
	United Arab Emirates	10	55	35	55	45
	Average	3	24	73	51	49
II	Mexico	21	33	46	47	53
Computed tomography (general)						
I	China, Taiwan Province	5	24	71	60	40
	Croatia	10	30	60	40	60
	Ecuador	6	24	70	50	50
	Norway	8	25	67	50	50
	Poland	11	21	68	52	48
	Romania	0	21	79	83	17
	Switzerland	3	19	78	53	47
	Ukraine	7	27	66	–	–
	United Arab Emirates	14	51	35	59	41
	Average	6	24	70	54	46
II	Mexico	14	37	49	48	52
	Turkey	16	46	38	57	43
	Average	15	42	43	53	47

Table 14 (continued)

Health-care level	*Country / area*	*Age distribution (%)*			*Sex distribution (%)*	
		0–15 years	*16–40 years*	*>40 years*	*Male*	*Female*
IV	United Republic of Tanzania	5	35	60	50	50
Angiography (cerebral)						
I	Australia	1	10	89	55	45
	Czech Republic	4	22	74	56	44
	Japan	0	16	84	54	46
	Kuwait	0	28	72	67	33
	Panama	17	25	58	70	30
	Poland	8	30	62	59	41
	Slovakia	6	41	53	52	48
	Sweden	2	27	71	50	50
	Switzerland	2	22	76	50	50
	Average	1	19	80	54	46
Angiography (cardiac)						
I	Australia	1	2	97	66	34
	Czech Republic	0	5	95	76	24
	Japan	14	0	86	53	47
	New Zealand	0	7	93	71	29
	Panama	17	24	59	66	34
	Poland	4	7	89	78	22
	Slovakia	7	41	52	50	50
	Sweden	2	7	91	70	30
	Switzerland	1	11	88	62	38
	Average	7	4	89	62	38
Angiography (other)						
I	Australia	1	5	94	60	40
	Croatia	0	25	75	55	45
	Czech Republic	6	9	85	66	34
	Japan	4	1	95	64	36
	Kuwait	0	28	72	67	33
	Panama	4	22	74	42	58
	Poland	11	17	72	38	62
	Slovakia	12	40	48	55	45
	Sweden	2	10	88	50	50
	Switzerland	1	17	82	55	45
	Average	5	6	89	60	40
II	Mexico	0	30	70	55	45
Angiography (general)						
I	Bahrain	4	45	51	63	37
	China, Taiwan Province	4	20	76	60	40
	Ecuador	30	40	30	55	45
	Poland	8	15	77	54	46
	Romania	0	25	75	92	8
	South Africa [M22]	2	23	75	70	30
	Switzerland	1	15	84	57	53
	Average	5	17	78	60	40
II	Mexico	6	38	56	59	41
	Turkey	9	51	40	59	41
	Average	7	43	50	59	41
Interventional (PTCA)						
I	Slovakia	6	44	50	48	52
	Sweden	0	15	85	75	25
	Switzerland	0	3	97	79	21
	Average	1	12	87	74	26

Table 14 (continued)

Health-care level	*Country / area*	*Age distribution (%)*			*Sex distribution (%)*	
		0–15 years	*16–40 years*	*>40 years*	*Male*	*Female*
Interventional (other)						
I	Sweden	2	11	87	60	40
	Switzerland	1	14	85	58	42
	Average	1	13	86	59	41
Interventional (general)						
I	Czech Republic	9	16	75	59	41
	Ecuador	7	60	33	50	50
	Kuwait	2	43	55	69	31
	Poland	7	19	74	59	41
	Switzerland	0	12	88	63	37
	United Arab Emirates	1	80	19	15	85
	Average	8	16	76	59	41
II	Mexico	9	51	40	39	61
	Turkey	4	36	60	51	49
	Average	8	48	44	41	59
Pelvimetry						
I	Australia	2	97	1	1	99
	Bahrain	1	97	1	10	90
	Czech Republic	3	87	10	15	85
	Ecuador	0	82	18	0	100
	Japan	0	100	0	0	100
	Kuwait	0	98	2	0	100
	Sweden	0	98	2	0	100
	United Arab Emirates	0	100	0	0	100
	Average	0.1	99.5	0.4	0.1	99.9
II	Mexico	8	82	10	22	78
	Turkey	0	100	0	0	100
	Average	8	82	10	22	78
III	Sudan	0	100	0	0	100
Other examinations						
I	Australia (CT extremities)	8	38	54	50	50
	Australia (tomography)	2	26	72	54	46
	Australia (ribs)	5	33	62	50	50
	Australia (arthrography)	4	32	64	58	42
	Poland (densitometry)	3	55	42	2	98
	Romania (hysterosalpingography)	0	100	0	0	100
	Romania (lung tomog.)	13	33	54	68	32
	Switzerland (bone mineral dens.)	1	1	98	6	94
	Switzerland (tomography)	0	30	70	44	56
All medical [b] x rays						
I	Australia	10	27	63	45	55
	Bahrain	24	42	34	62	38
	Czech Republic	13	25	62	45	55
	Ecuador	26	43	31	54	46
	Kuwait	17	59	24	63	37
	Netherlands	7	18	74	45	55
	Panama	13	26	61	47	53
	Poland	–	–	–	52	48
	Romania	10	41	49	56	44
	Slovakia	17	38	45	50	50
	Sweden	9	20	71	40	60
	Switzerland	9	19	72	46	54
	Average	11	29	60	49	51

Table 14 (continued)

Health-care level	*Country / area*	*Age distribution (%)*			*Sex distribution (%)*	
		0–15 years	*16–40 years*	*>40 years*	*Male*	*Female*
II	Mexico	20	43	37	52	48
III	Morocco	16	54	30	43	57
Dental (intraoral)						
I	Ecuador	8	73	19	31	69
	Japan	8	32	60	45	55
	Poland	5	56	38	45	55
	Romania	11	54	35	44	56
	Slovakia	10	53	37	45	55
	Switzerland	5	38	57	45	55
	Average	8	33	59	45	55
IV	United Republic of Tanzania	25	35	40	–	–
Dental (panoramic)						
I	Ecuador	16	66	18	48	52
	Japan	8	40	52	44	56
	Poland	7	49	44	54	46
	Slovakia	13	45	42	46	54
	Switzerland	21	39	40	45	55
	Average	8	40	52	44	56
II	Mexico	33	50	17	36	64
Dental (general)						
I	Bahrain	21	33	46	59	41
	Ecuador	8	73	19	31	69
	Poland	6	56	38	45	55
	Romania	11	54	35	44	56
	Slovakia	11	52	37	45	55
	Switzerland	9	38	53	45	55
	Average	8	47	45	45	55
IV	United Republic of Tanzania	25	35	40	–	–

a No data available.
b Excluding dental x-ray examinations.

The entries in this Table are qualified as follows:

Brazil: Survey data for Paraná State (with a population of 9 million and a social and economic profile above the average for Brazil).
China, Taiwan Province: Data for 'Upper GI tract' relate to all barium studies.
Costa Rica: Data from Hospital Calderón Guardia (serving one-third of the population).
Czech Republic: Survey data relating to Prague (about 10% of national population).
New Zealand: Data from one large teaching hospital in public sector.
Romania: Data from 8 counties in East and South-East of country (with population of about 5.7 million).
Slovakia: Survey data relating to population base of about 660,000.
Sweden: Survey data from a small sample of health districts.
Turkey: Survey data from Hacettepe University Hospital, Atatürk University Hospital, Gülhane Military Hospital and Ankara University Hospital.

Table 15
Typical effective doses to patients undergoing some common types of diagnostic medical [a] x-ray procedures (1991–1996)
Data from UNSCEAR Survey of Medical Radiation Usage and Exposures unless otherwise indicated

PART A

Country	*Typical effective dose per procedure [b] (mSv)*												
	Chest			*Limbs and joints*	*Spine*			*Pelvis and hips*	*Head*	*Abdomen*	*GI tract*		*Chole-cysto-graphy*
	Radio-graphy	*Photo-fluorography*	*Fluoro-scopy*		*Lumbar*	*Thoracic*	*Cervical*				*Upper*	*Lower*	
Health-care level I													
Australia	0.025 (±0.008)	– [c]	–	–	2 (±1)	–	–	0.6	–	1 (±0.7)	–	–	–
Belarus	0.25 (30–50%)	0.5 (30–50%)	1.0 (30-50%)	0.2 (30-50%)	1.1 (30-50%)	1.6 (±30-50%)	1.1 (30-50%)	1.1 (30-50%)	0.12 (30-50%)	1.4 (30-50%)	0.6 (30-50%)	1 (30-50%)	0.2 (30-50%)
Bulgaria	0.16 (0.04-0.18)	0.91 (0.77–1.05)	1.85 (1.6–2.1)	–	–	–	–	–	–	–	–	–	–
China, Taiwan Prov.	0.02	–	–	–	0.48	–	–	–	–	0.19	3.8	4.1	–
Czech Republic	0.05	0.7	–	–	2	1.76	0.28	1.26	0.28	3	3	8.5	1.26
Finland	0.1	–	–	–	2.3	1	0.2	1.3	0.1	2.2	9	9.7	–
Germany	0.3 (0.01–5.5)	–	–	0.06 (0.001-0.5)	2	0.7	0.2	0.8 (0.1-4.8)	0.03 (0.001-0.7)	1.2 (0.1-5.3)	8.3 (0.1-38)	17.7 (0.2-85)	7.1 (0.7-36)
Japan	0.057	0.053	1.14	–	1.45	0.65	0.26	0.58	0.09	0.24	3.33	2.68	0.88
Netherlands	0.06 (±0.08)	–	–	–	2	1	1	1	0.1	1	6.4 (±3.4)	4.7 (±2.4)	–
New Zealand	–	–	–	–	–	–	–	–	–	–	5	10	–
Norway	0.13	0.23	–	–	1.1	0.5	0.2	0.5	0.2	1	4	8	–
Panama	0.021 (±0.013)	–	–	0.003 (±0.003)	2.17 (±1.0)	1.20 (±0.43)	0.07 (±0.01)	0.44 (±0.13)	0.045 (±0.02)	0.30 (±0.12)	6.9 (±2.9)	3.12 (±0.76)	0.87 (±0.14)
Poland	0.11	0.82	4.1	0.02	4.33	3.03	–	0.61	0.1	2.2	14	22.7	–
Romania	0.25 (±0.11)	0.63 (±0.3)	0.95 (±0.4)	0.08 (±0.03)	3 (±1.4)	2.1 (±1.2)	0.21 (±0.1)	2.6	0.17 (±0.12)	1.9 (±1)	4.1 (±1.9)	9 (±3.8)	1.6 (±0.9)

Table 15 (continued)

Country	*Typical effective dose per procedure [b] (mSv)*												
	Chest			*Limbs and joints*	*Spine*			*Pelvis and hips*	*Head*	*Abdomen*	*GI tract*		*Chole-cysto-graphy*
	Radio-graphy	*Photo-fluorography*	*Fluoro-scopy*		*Lumbar*	*Thoracic*	*Cervical*				*Upper*	*Lower*	
Russian Federation	0.4	0.67	–	–	–	–	–	–	–	–	3.3	–	–
Sweden	0.15	–	–	0.1	3	1	0.2	1.5	0.1	2.5	3	8	6
Switzerland	0.1 (±0.03)	0.5 (±0.2)	0.2 (±0.1)	0.05 (±0.05)	1.5 (±0.5)	0.8 (±0.5)	0.2 (±0.2)	1 (±0.5)	0.1 (±0.1)	0.5 (±0.3)	5 (±4)	5 (±4)	8 (±4)
United Arab Emirates	0.059	0.018 (0.011-0.028)	–	–	0.47	0.35	0.28	0.35 (0.11-0.67)	1.06	0.43	4.4	9.8	–
United Kingdom	0.02	–	–	–	1.3	0.7	–	0.7	0.04	0.7	2.6	7.2	–
Average [d]	0.14	0.65	1.08	0.06	1.8	1.4	0.27	0.83	0.07	0.53	3.6	6.4	2.3
Health-care level II													
Brazil	0.053	–	–	–	–	–	–	–	–	0.5 (± 0.36)	–	–	–
Malaysia [N26]	0.03	–	–	0.04	1.04	0.46	0.03	0.74	0.04	1.05	6	–	1.5
Average	0.05	–	–	0.04	1.0	0.46	0.03	0.74	0.04	0.62	6	–	1.5

PART B

Country	*Typical effective dose per procedure (mSv)*											
	Urography	*Mammography*			*Computed tomography*			*Angiography*			*PTCA*	*Total of all medical examinations*
		Screening	*Clinical*	*All*	*Head*	*Body*	*All*	*Cerebral*	*Cardiac*	*All*		
Health-care level I												
Australia	–	–	–	0.4 (±0.16)	2.6 (±2.0)	10.6 (±7.5)	6.9	–	–	–	–	1.33
Belarus	2 (±30-50%)	–	–	–	–	–	–	–	–	–	–	–
Bulgaria	–	–	–	–	–	–	–	–	–	–	–	1.28
Canada	–	–	–	–	–	–	–	–	–	–	–	1.05

Table 15 (continued)

Country	*Typical effective dose per procedure (mSv)*											
	Urography	*Mammography*			*Computed tomography*			*Angiography*			*PTCA*	*Total of all medical examinations*
		Screening	*Clinical*	*All*	*Head*	*Body*	*All*	*Cerebral*	*Cardiac*	*All*		
China, Taiwan Prov.	–	–	–	–	–	–	–	–	–	–	–	0.43
Czech Republic	2.04	–	0.5	–	1.1	9.2	3.8	2.8	3.6	7.3	–	–
Denmark	–	–	–	–	–	–	–	–	–	–	–	0.7
Finland	4.5	0.1	0.2	–	1.3	7.9	3.8	–	14.8	–	–	0.64
Germany	4.9 (0.2–19)	–	–	0.5 (0.1–2)	2.6 (1–5)	15.4 (4–50)	11.3	–	–	12.3 (1–190)	23 (1–190)	1.5 (0.001–190)
Japan	2.47	–	–	–	–	–	–	–	5.56	–	–	–
Netherlands	4	0.1 [e]	0.1	0.1 [e]	1.7 [e]	10.2 [e]	6.7 [e]	–	5 [e]	5 [e]	5 [e]	1.0 [e]
New Zealand	–	–	0.07 (±0.02)	–	2.2 (±1.1)	7.8 (±4)	–	–	12.3 (±5.4)	–	16.2 (±9.2)	–
Norway	2	–	0.12	–	2	10	6.5	–	–	–	–	–
Panama	2.07 (±0.39)	–	–	0.24 (±0.11)	1.06 (±0.12)	3.8 (±0.51)	2.1	3.7 (±1.1)	–	–	–	–
Poland	3.1	–	–	1 (±0.3)	–	–	3.5	–	–	25	7	1.2
Portugal	–	–	–	–	–	–	–	–	–	–	–	0.83
Romania	5.8 (±2.9)	–	–	0.62 (±0.3)	–	–	–	–	–	0.22	–	1.35 (±0.63)
Russian Federation	–	–	–	0.56	0.4	5.8	–	–	–	–	–	0.73
Sweden	5	0.1	0.2	–	2	10	5.8	1	12	9.2	22	1.2
Switzerland	4 (±2)	–	–	0.1 (±0.1)	2 (±1)	5 (±2)	3.9	2 (±1)	10 (±1)	6.7	10	0.8 (±0.4)
Ukraine	–	–	–	–	–	–	–	–	–	–	–	0.83
United Arab Emirates	2.66	0.13	0.11 (0.01–0.14)	–	2.62 (1.75–3.3)	9.83 (6.8–11.8)	–	–	–	–	–	–
United Kingdom	2.4	0.06	–	–	2	9	6	–	–	–	–	–

Table 15 (continued)

Country	*Typical effective dose per procedure (mSv)*											
	Urography	*Mammography*			*Computed tomography*			*Angiography*			*PTCA*	*Total of all medical examinations*
		Screening	*Clinical*	*All*	*Head*	*Body*	*All*	*Cerebral*	*Cardiac*	*All*		
United Kingdom	2.4	0.06	–	–	2	9	6	–	–	–	–	–
United States	–	–	–	–	–	–	–	–	–	–	–	0.52
Average	3.7	0.07	0.21	0.51	2.3	13.3	8.8	2.0	7.3	12.4	22	0.83
Health-care level II												
Brazil	3.89 (±2.8)	–	–	–	–	–	–	–	–	–	–	0.26
China [Z10]	–	–	–	–	–	–	–	–	–	–	–	0.57
Malaysia [N26]	2.4	–	0.1	0.1	2.8	7.8	4.9	6.8	6.8	–	–	0.28
Average	3.9	–	0.1	0.1	2.8	7.8	4.9	6.8	6.8	–	–	0.56

a Excluding dental x-ray examinations.
b Variations shown in brackets (standard deviation, coefficient of variation or range).
c No data available.
d Frequency-weighted average of national values.
e These revised data were received by the Committee after completion of the global analysis.

The entries in this Table are qualified as follows:

Brazil: Survey data for Paraná State (with a population of 9 million and a social and economic profile above the average for Brazil).
China (Taiwan): Data for lumbar spine, GI tract and total of all medical examinations from reference [L23].
Germany: Mean effective dose for general classification of spine is 1.2 mSv (range: 0.1–20 mSv).
Malaysia: Data for chest, spine and head refer to AP/PA projections. Data for 'GI tract' relate to both 'Upper' and 'Lower' categories.
Norway: Data from national survey involving about 50 hospitals and 5000 measurements.
Romania: Additional survey data in relation to 'Chest fluoroscopy': mean entrance surface dose of 13.4 mGy and mean dose-area product of 3.6 mGy cm^2 [I28].
Russia: Additional survey data in relation to effective doses from 'Chest fluoroscopy': dose rates without and with electronic image intensification of 1.4 mSv per minute and 0.9 mSv per minute, respectively. Data shown for 'GI tract' relate to both 'Upper' and 'Lower' categories. Effective dose rates from fluoroscopy without and with electronic image intensification of 4.2 mSv per minute and 2.3 mSv per minute, respectively during upper GI examinations, and 3.6 mSv per minute and 2.2 mSv per minute, respectively, during lower GI examinations. Data for 'CT - Body' refer to examinations of the abdomen; mean effective dose for CT chest is 2.8 mSv.
United Arab Emirates: Survey data from one hospital, except those for chest radiography and pelvis/hip (from seven hospitals), and chest photofluorography (from four units at two hospitals).

Table 16
Patient dose from diagnostic x-ray examinations
Data from UNSCEAR Survey of Medical Radiation Usage and Exposures unless otherwise indicated

PART A

Country / area	*Scope of data*	*Dose quantity* [a]	*Mean value of dose quantity per radiograph* [b]										
			Skull		*Chest*		*Thoracic spine*		*Lumbar spine*			*Abdomen*	*Pelvis*
			AP / PA	*LAT*	*PA*	*LAT*	*AP*	*LAT*	*AP*	*LAT*	*LSJ*	*AP*	*AP*
Health-care level I													
Australia [B29]	State	ESD	1.9 (0.9–2.7)	1.2 (0.5–2.3)	0.12 (0.02-0.21)	0.63 (0.22-1.42)	– [c]	–	6.1 (2.3–19.7)	15.1 (3.7–32.5)	22.4 (5.3–43.3)	4.2 (1.4–7.3)	3.9 (1.5–7.0)
Argentina [I4]	3 hospitals	ESD ESD	–	–	0.38 (pre) (0.24-0.48) 0.33 (post) (0.31-0.34)	–	–	–	–	–	–	5.10 (pre) 3.31 (post)	–
Canada	Regional	ESD ESD	–	0.68 (man.) (± 0.23) 0.74 (auto.) (± 0.21)	0.11 (man.) (± 0.03) 0.13 (auto.) (± 0.04)	–	1.82 (man.) (± 0.6) 1.50 (auto.) (± 0.05)	–	3.34 (man.) (± 1.0) 3.69 (auto.) (± 1.3)	–	–	2.35 (man.) (± 0.5) 1.64 (auto.) (± 0.5)	–
China, Taiwan Province [Y9]	National	E	–	–	0.040 (± 0.12)	–	–	–	–	–	–	0.21 (± 0.10)	–
Czech Republic [I4]	3 hospitals	ESD ESD	–	–	0.41 (pre.) (0.08-0.99) 0.12 (post.) (0.1-0.13)	–	–	–	8.36 (pre.) (5.56-10.8) 5.64 (post.) 3.87-8.39)	–	–	–	6.37 (pre.) (5.59-6.99) 4.12 (post.) 3.09-6.99)
Estonia [S29]	4 hospitals	ESD	15.1 (2.2–30.1)	8.1 (1.1–14.3)	0.30 (0.15-0.49)	0.86	–	–	13.8 (0.84-31.7)	30.3 (7.3–61.0)	–	14.0 (2.2–26.8)	15.8 (2.5–29.9)
Finland [R11]	National	ESD DAP E	3.37 (1.06-8.53) 1.63 (020-5.82) 0.12 (0.03-0.42)	1.93 (0.57-8.01)	0.24 (0.06-3.28) 0.44 (0.08-3.47) 0.10 (0.03-1.10)	0.73 (0.15-4.44)	4.89 (0.49-11.3) 4.14 (1.10-22.2) 1.02 (0.23-3.92)	11.6 (2.10-26.2)	8.80 (0.49-43.5) 8.25 (0.88-68.8) 2.27 (0.25-11.4)	18.2 (2.10-111)	–	7.08 (0.76-19.0) 6.90 (0.86-20.8) 2.22 (0.60-5.89)	6.15 (2.02-22.0) 3.80 (0.79-16.0) 1.25 (0.31-4.49)
Germany [B9]	National	DAP	1.07		1.37		3.51		9.32			3.62	3.62
Greece [O3]	1 hospital	ESD E	3.5 (± 1.95) 0.094	2.68 (± 1.49) 0.034	0.69 (± 0.4) 0.11	2.94 (± 1.57) 0.22	8.25 (± 4.63) 0.74	10.9 (±8.1) 0.33	18.9 (± 6.76) 1.88	44.9 (± 22.9) 0.94	–	11.2 (± 7.3) 1.45	12.5 (± 6.85) 1.35

Table 16 (continued)

Country / area	*Scope of data*	*Dose quantity* [a]	*Mean value of dose quantity per radiograph* [b]										
			Skull		*Chest*		*Thoracic spine*		*Lumbar spine*			*Abdomen*	*Pelvis*
			AP / PA	*LAT*	*PA*	*LAT*	*AP*	*LAT*	*AP*	*LAT*	*LSJ*	*AP*	*AP*
Ireland [J10]	National	ESD	–	–	0.22 (0.02-0.65)	–	–	–	6.47 (0.27-20.3)	16.9 (1.8–67.1)	36.9 (1.5–102)	4.75 (0.5–18.3)	5.63 (1.2–26.5)
Lithuania	National	ESD	2.11	2.73	0.81	1.39	–	–	22.8	35.5	37.4	20.43	21.43
Norway [O6]	National	DAP E	–	–	0.64 0.12	–	–	–	–	–	–	7.61	3.48
Panama	National	ESD	–	–	0.17 (±0.10)	–	–	–	–	–	–	2.33 (±0.91)	3.28 (±1.0)
Poland	National	ESD E	–	–	0.20 (0.16-2.76) 0.06 (0.06-0.49)	0.88 0.10	5.1 (0.7-18.5) 0.9 (0.63-12.6)	8.3 (1.2-23.2) 2.13 (0.98-8.9)	7.50 (1.38-25.3) 3.43 (0.77-11.5)	12.0 (3.45-38.4) 0.9 (0.71-2.27)	–	4.7 (0.75-23.2) 2.18 (0.12-7.12)	2.54 (1.97-25.8) 0.61 (0.40-10.3)
Romania [I28]	21 hospitals	ESD	11.0 (1.0–31)	9.4 (1.2–28)	1.7 (0.3–6.0)	4.2 (0.7–13)	11.2 (2.0–41)	24.0 (3.5–97)	17.6 (2.0–71)	42.0 (4.4–162)	–	10.9 (2.1–37)	13.2 (1.9–35)
Russian Federation	National	E	–	–	0.4	0.6	0.8	0.3	1.7	1.2	–	–	0.75
New Zealand	National	ESD DAP E	3.0 (± 2.04) 0.96 (± 0.65) 0.03 (± 0.02)	1.56 (± 1.04) 0.57 (± 0.37) 0.02 (± 0.05)	0.22 (± 0.25) 0.17 (± 0.2) 0.03 (± 0.03)	1.24 (± 1.92) 0.62 (± 0.67) 0.1 (± 0.11)	4.32 (± 2.67) 1.54 (± 1.01) 0.44 (± 0.26)	13.3 (± 9.72) 3.53 (± 2.68) 0.31 (± 0.21)	5.47 (± 2.89) 1.88 (± 1.16) 0.6 (± 0.33)	18.9 (± 11.6) 3.92 (± 2.33) 0.47 (± 0.29)	31.2 (± 21.8) 3.83 (± 2.79) 0.36 (± 0.24)	4.57 (± 2.57) 2.67 (± 1.61) 0.58 (± 0.33)	3.98 (± 2.33) 2.37 (± 1.49) 0.63 (± 0.38)
Slovenia	Local	ESD E	–	–	0.29 0.05	1.02 0.06	4.89 0.37	7.22 0.21	6.11 0.63	15.65 0.48	15.00 0.14	3.52 0.04	4.72 0.65
South Africa [M22, H29]	National	ESD	6.4	3.6	1.5	3.2	13.1	35.6	27.3	59.1	–	13.1	15.4
United Arab Emirates	Local	E	0.68	0.38	0.020 (0.005-0.028)	0.039 (0.0084–0.094)	–	–	–	–	–	–	–
United Kingdom [H11]	National	ESD E	3.0 (0.5–10.0) 0.03	1.5 (0.56-4.43) 0.01	0.16 (0.01-0.94) 0.02	0.57 (0.11–2.6) 0.04	4.7 (1.3–18.0) 0.40	13.0 (1.3–43.0) 0.29	6.1 (1.4–31.0) 0.69	16.0 (3.9–75.0) 0.29	29.0 (4.2–84.0) 0.29	5.6 (0.75-16.6) 0.7	4.4 (1.0–16.0) 0.66
United States	National	ESD	–	–	0.15	–	–	–	–	–	–	–	–

Table 16 (continued)

Country / area	*Scope of data*	*Dose quantity* [a]	*Mean value of dose quantity per radiograph* [b]										
			Skull		*Chest*		*Thoracic spine*		*Lumbar spine*			*Abdomen*	*Pelvis*
			AP / PA	*LAT*	*PA*	*LAT*	*AP*	*LAT*	*AP*	*LAT*	*LSJ*	*AP*	*AP*
Health-care level II													
Brazil	3 hospitals	ESD E	4.55 (3.08-7.34)	–	0.33 0.021 (±0.01)	1.01 0.032 (±0.02)	–	–	6.82 (4.36–9.38)	–	–	7.88	5.28 (4.35-6.20)
Costa Rica	1 hospital	ESD	4.45 (±2.3)	2.92 (±2.4)	1.97 (±2.3)	5.33 (±5.3)	7.14 (±4.6)	12.4 (±8.9)	10.6 (±12.0)	27.9 (±18.1)	–	7.74 (±5.3)	6.39 (±3.3)
Iran (Islam. Rep. of) [I4]	2 hospitals	ESD ESD	–	–	0.21 (pre.) (0.19-0.26) 0.06 (post.) (0.04-0.09)	–	–	–	–	–	–	3.57 (pre.) (2.83-4.25) 1.87 (post.) 1.47–2.08)	–
Malaysia [N15, N26]	12 hospitals	ESD E	4.78 0.04	3.34 0.04	0.28 0.03	1.40 0.09	7.03 0.46	16.5	10.6 1.04	18.7	–	10.0	8.41
Peru	–	ESD	3.5 (±1.0)	–	0.4 (± 0.3)	–	–	–	7.0 (±3.0)	–	–	8.5 (± 2.0)	6.0 (± 3.0)
Turkey	Local	ESD	4.27 (± 0.88)	–	0.32 (± 0.05)	0.70 (± 0.20)	7.45 (± 0.54)	–	2.81 (± 1.49)	–	–	10.73 (± 2.01)	19.35 (± 1.16)
Health–care level III													
Egypt [H28]	14 hospitals	ESD	0.3	–	0.5	–	–	–	3.3	–	–	1.5	1.5
Ghana [S39]	12 hospitals	ESD E	5.7 (2.7–9.1) 0.08 (±38%)	–	0.74 (0.1–1.5) 0.10 (±61%)	–	–	–	9.2 (3.1–16.0) 1.61 (±52%)	–	–	–	7.9 (2.0–13.1) 1.71 (±40%)
Indonesia [L19]	4 hospitals	ESD	3.61 (± 1.24)	3.52 (± 1.48)	0.51 (± 0.18)	–	–	–	6.30 (± 1.50)	9.36 (± 3.0)	9.57 (± 6.22)	–	3.72 (±1.23)
Morocco	–	ESD	9.39 (± 2)	–	0.23 (± 0.2)	0.72 (± 0.2)	–	–	12.3	–	–	–	10.2
Thailand [L19]	4 hospitals	ESD ESD	1.37 (pre.) (± 0.76) 0.72 (post.) (± 0.26)	1.10 (pre.) (± 0.64) 0.52 (post.) (± 0.17)	0.26 (pre.) (± 0.16) 0.16 (post.) (± 0.09)	0.97 (pre.) (± 0.48) 0.52 (post.) (± 0.27)	–	–	2.81 (pre.) (± 2.1) 1.21 (post.) (± 0.65)	7.97 (pre.) (± 5.3) 4.08 (post.) (± 3.5)	–	–	1.52 (pre.) (± 1.09) 0.93 (post.) (± 0.47)

Table 16 (continued)

Country / area	*Scope of data*	*Dose quantity* [a]	*Mean value of dose quantity per radiograph* [b]										
			Skull		*Chest*		*Thoracic spine*		*Lumbar spine*			*Abdomen*	*Pelvis*
			AP / PA	*LAT*	*PA*	*LAT*	*AP*	*LAT*	*AP*	*LAT*	*LSJ*	*AP*	*AP*
Health-care level IV													
Ethiopia [I4]	2 hospitals	ESD ESD	–	–	1.34 (pre.) (0.94-1.74) 0.57 (post.) (0.43-0.70)	–	–	–	–	–	–	–	5.26 (pre.) 5.11–5.41) 10.57(post) (9.74-11.4)
Unitd Rep. of Tanzania [M37]	5 hospitals	ESD	–	–	0.5 (± 0.3)	–	–	–	7.7 (± 3.8)	17.5 (± 8.5)	–	8.3 (± 5.6)	6.4 (± 4.5)

PART B

Country	*Scope of data*	*Dose quantity* [a]	*Mean value of dose quantity per examination* [b]						
			Upper GI tract		*Lower GI tract*		*Urography*	*ERCP*	*Venogram*
			Swallow	*Meal*	*Enema*	*Colonoscopy*			
Health-care level I									
Germany [B9]	National	DAP	13.05	35.9	61.5	–	20.3	33.7	7.8
Iceland [W42]	5 hospitals	DAP	–	–	(43.6–77.4)	–	–	–	–
New Zealand	National	E	–	3	9	0.4	–	4	–
Norway [O6]	National	DAP E	7.41 1.5	24.8 5.9	49.1 13.7	–	18.1 3.8	31.8 8.3	–
Romania [I18] [I28]	5 hospitals 21 hospitals	DAP E DAP	–	37.7 (± 17.5) 3.7 22.0 (2–100)	32.2 (± 3.3) 8.12 34.7 (2–116)	–	–	–	–
Switzerland [M45]	–	DAP	13.5 (± 10.2)	68.5 (± 42.9)	–	–	–	37.1 (± 32.8)	–
United Kingdom [H11] [B56]	National Regional	DAP DAP	9.3 5.63	13.0 7.60	25.8 15.7	–	13.4 –	– 9.0	3.8 1.92

a ESD: entrance surface dose with backscatter (mGy); DAP: dose-area product (Gy cm^2); E: effective dose (mSv).
b Variations shown in brackets (standard deviation or range).
c No data available.

Table 16 (continued)

The entries in this Table are qualified as follows:

Argentina: Pairs of values represent surveys before and after the introduction of a programme of quality control. Interhospital variation in brackets.
Brazil: Survey data for Paraná State (with a population of 9 million and a social and economic profile above the average for Brazil); data for skull, lumbar spine, and pelvis from reference [I4].
Brazil: Pairs of values represent surveys before and after the introduction of a programme of quality control. Interhospital variation in brackets.
Canada: Survey data from Manitoba (4% of Canadian population) for standard pressed wood phantoms (unit density) under manual and automatic exposure control and for rare-earth intensifying techniques.
Costa Rica: Data from Hospital Calderón Guardia (serving one-third of the population).
Czech Republic: Pairs of values represent surveys before and after the introduction of a programme of quality control. Interhospital variation in brackets.
Egypt: Maximum recommended doses derived from the following published maximum entrance surface exposures: 26 mR skull; 45 mR chest; 272 mR lumbar spine; 125 mR abdomen; 125 mR pelvis [H28].
Estonia: Interhospital variation in brackets.
Ethiopia: Pairs of values represent surveys before and after the introduction of a programme of quality control. Interhospital variation in brackets.
Finland: DAP and E data represent mean values for complete examinations.
Germany: DAP data refer to complete examinations (rather than doses per radiograph).
Ghana: Data for AP pelvis also includes radiography of the abdomen.
Iceland: Data for barium enema examinations refer to range of mean DAP values observed in survey of 5 hospitals.
Iran (Islamic Rep. of): Pairs of values represent surveys before and after the introduction of a programme of quality control. Interhospital variation in brackets.
Lithuania: Data from Vilnius University Hospital.
Morocco: Data from IAEA Coordinated Research Programme.
Norway: Data for 'Upper GI- Meal' and 'Lower GI - Enema' refer to double contrast technique (corresponding data for single contrast technique: 14.0 Gy cm^2 & 3.4 mSv, and 32.3 Gy cm^2 & 9.0 mSv, respectively).
Peru: Data may refer to complete examinations.
Romania: Pairs of values represent surveys before and after the introduction of a programme of quality control. Inter-hospital variation in brackets.
South Africa: Derived from free-in-air data calculated for average exposure conditions.
United Rep. of Tanzania: Survey data for 500 patients per examination spread over 4 referral hospitals and 1 regional hospital; these hospitals are collectively responsible for nearly 50% of the annual national total of patients examined with x-rays.
Thailand: Pairs of values represent surveys before and after the introduction of a programme of quality control.
Turkey: Survey data from Ankara University Hospital and Gülhane Military Hospital.
United Arab Emirates: Survey data for 'Head' examinations from one hospital, data for 'Chest' from seven hospitals.
United Kingdom: Inter-hospital variation in brackets. Data from reference [B56] represent median values from regional survey.
United States: On the basis of entrance surface exposure of 0.12 mGy from NEXT programme for 1994.

Table 17
Patient dose per procedure from diagnostic angiographic examinations

Procedure	*Technique*	*Fluoroscopy time [a] (min)*	*Dose-area product [a] (Gy cm²)*	*Effective dose [a] (mSv)*	*Ref.*
Coronary	Children [b]	–	13.3 (1.4–98)	–	[B48]
	Cine film [c]	8 (70 max.)	41 (228 max.)	–	[H6]
	Cine film [d]	4.3 (1.5–15)	(21–40)	(2–9)	[C22]
	-	3.9	16.1 [h]	3.1 (1–12)	[L3]
	Cinefluorography [e]	7 (SD 3.6)	–	10.6	[K5]
	-	–	55.9	–	[Z12]
	-	9.8 (± 65%)	30.4 (± 57%)	5.6	[B3]
	-	–	38.9	8.9	[O6]
	Digital cine [f]	5.7	47.7	9.4	[B54]
	-	–	58.7 [i]	–	[W41]
	No. frames [a]: 878 (302 SD)	3.6 (3.3 SD)	39.3 (18 SD)	–	[P20]
	Cine film [g]	(3.1–5.6)	(23–79)	(4.6–15.8)	[N29]
Cerebral	DSA	4.7	48.5	3.6	[M9]
	–	–	–	Eye/thyroid data [k]	[H24]
	DSA/conventional [j]	–	–	10.6 (2.7–23.4)	[F15]
	Carotid (DSA)	3.9 (1.2–11.8)	27.4 (9.5–80)	4 (1–12)	[S3]
	DSA/conventional	15 (± 10)	59 (12–120)	–	[K23]
	Digital	12.1 (2.9–36)	74 (21–196)	7.4 (2.1–19.6)	[M34]
	–	–	55.2	1.6	[O6]
	–	–	50	–	[V14]
	Carotid	7.8 (3.1–17.9)	98 (44–208)	–	[M46]
Abdominal	Hepatic (DSA)	10.3 (2.3–28.6)	137 (28–279)	23 (4–48)	[S3]
	Renal (DSA)	12.1 (5.5–21)	95 (41–186)	16 (6–34)	[S3]
	Renal (DSA)	5.1	43	6	[K26]
	Mesenteric and/or coeliac art.	14.7	65	10	[K26]
	DSA/conventional	1.0 (± 0.5)	57 (31–89)	–	[K23]
	Digital	8.0 (1.8–27)	118 (21.6–301)	18.9 (3.5–48)	[M34]
	Renal angiography	5.1 (2.9–7.6)	39.8 (17.4–72)	6.4 (2.8–11.5)	[M34]
	Renal angiography	2.8 (0.5–9.3)	177 (90–327)	–	[M46]
	Digital	6.7 (± 6.5)	61 (8–192)	8.2	[R17]
	Aortagram	–	98 (297 max.)	–	[W32]
	Mesenteric	–	112 (352 max.)	–	[W32]
Peripheral	Femoral (DSA)	3.7 (1.2–19)	42.9 (13–122)	4 (1–16)	[S3]
	Aorto–iliac + 1 leg	2.9 (± 2.8)	13 (2–52)	–	[K23]
	Aorto–iliac + 2 legs	4.5 (± 1.2)	32 (19–68)	–	[K23]
	Aorto–iliac + thighs	1.2 (± 0.4)	47 (16–100)	–	[K23]
	Aortogram/femoral runoff	3.9 (1.8–10.8)	–	14.0 (7.0–21.8)	[C23]
	Femoral arteriogram	2.4 (± 1.9)	26	4	[T8]
	Femoral (DSA/conventional)	1.7 (0.4–6.7)	24.4 (5.6–100)	2.7	[H25]
	Femoral (DSA)	2.3 (0.9–13.7)	74 (19.8–184)	9.0	[H25]
	Femoral (DSA)	–	13	3.1 (± 1.8)	[C24]
	Femoral	7.2 (1.8–17.2)	46.7 (3–114)	7.5 (0.5–18.2)	[M34]
	Femoral	2.4 (13–8.3)	16 (8–91)	–	[M46]
	Lower limbs	3.7 (± 3.1)	30 (9–77)	6.2	[R17]
	Lower limbs (arteries)	–	35.5	6.4	[O6]
	Lower limbs (veins)	–	4.9	0.9	[O6]
	Lower limb	–	78 (306 max.)	–	[W32]
	Venography (arm)	–	23 (57 max.)	–	[W32]

a Mean values of parameters (with range, standard deviation, or coefficient of variation in parentheses).
b Ages 0.01-12 years. Calculated entrance surface doses: mean 99 mGy, range 10-526 mGy.
c Mean length of cine film 28 m (maximum 85 m).
d Range of cine film length: 25-100 m.
e Mean time of cinefluorography (25-30 frames per second) was 60 seconds (standard deviation 30 seconds).
f Mean number of frames: 689.
g Range of cine film length: 16-43 m.
h 61% of total DAP from radiography.
i Data refer to right and left heart angiography.
j Mean contributions to effective dose: 67% from fluoroscopy, 26% from cut films, and 7% from DSA.
k Maximum dose to right ocular lens of 125 mGy; maximum dose to thyroid of 88 mGy.

Table 18
Patient dose per procedure [a] during interventional radiology

Procedure	*Fluoroscopy time (min)*	*Localized dose to skin (Gy)*	*Dose-area product (Gy cm²)*	*Effective dose (mSv)*	*Ref.*
PTCA (Percutaneous transluminal coronary angioplasty)	11.5 (2.4–28)	– [e]	93 (33–402)	28.9 (7.5–57)	[N6]
	30 (9–70)	0.15 (0.05–0.3)	28.5 (20–50.5)	–	[F4]
	15	1	–	10	[P3]
	(56 max.)	–	–	–	[K5]
	11 (92 max.)	–	42 (266 max.)	–	[H6]
	31.3	–	–	–	[G4]
	43.8 [b]	–	–	–	[G4]
	31 [c] (8–62)	0.46 [c]	–	–	[B6]
	43 [d] (3–53)	0.39 [d]	–	–	[B6]
	–	(1–5)	–	–	[H7]
	–	0.1 (1 max.)	87.5 (67–122)	–	[V3]
	–	–	110 (40–340)	–	[B9]
	–	–	143 (83 SD)	–	[B10]
	–	–	–	22	[L4]
	18.7	1.1	–	–	[P15]
	–	–	91.8	–	[Z12]
	21 (± 63%)	0.038 (at spine)	37.6 (± 41%)	6.9	[B3]
	12.4	–	72.2	14.2	[B54]
	–	0.5 (0.01–2.2)	–	–	[V14]
	–	–	45.8	–	[W41]
	18.5 (15.5 SD)	0.14 (LAO proj.)	102 (85 SD)	–	[P20]
PTA (Percutaneous transluminal angioplasty)	14	0.4	75	10	[S14]
	19.7 (5.3–26)	–	68.5 (22–150)	–	[F5]
	(21.8–68) [f]	–	–	–	[N6]
	6	–	65.1	–	[F6]
	–	–	43.5 (5–184)	–	[B9]
	24 [b] (5–45)	0.3 [b]	140 [b] (73–223)	12.5 [b]	[H27]
	–	–	67.3 (289 max.)	–	[W32]
	17.9 (6.9–57.3)	–	68 (15–338)	–	[M46]
	(6.3–26.3)	–	(19–109)	–	[K50]
TIPS (Transjugular intrahepatic portosystemic shunt)	46	–	–	–	[M8]
	–	–	354	–	[V3]
	48.4 (21.7–100)	–	525 (273–1131)	83.9 (43.7–181)	[M34]
	32 (9–79)	1.7	226 (111–354)	27 (14–44)	[Z11]
	59 (26–115)	0.4	77 (7–240)	8 (2–40)	[Z11]
	48	1.2 (5 max.)	220	50	[S14]
	–	–	182 (470 max.)	–	[W32]
Radiofrequency ablation	42 (27–108)	–	116 (26–217)	–	[N6]
	50 (31 SD)	–	–	17	[L4]
	21.4 (142 max.)	0.9 (6.2 max.)	–	–	[B7]
	(190 max.)	(8.4 max.)	–	–	[C3]
	28 (3–109)	–	103 (7–516)	–	[F6]
	–	0.07 (1.4 max.)	–	–	[C9]
	–	–	56.4 [g] (12–184)	–	[H8]
	–	–	77.5 [h] (13–367)	–	[H8]
	–	–	97.3 [i] (9–532)	–	[H8]
	53 (± 50)	1.3 (± 1.3)	–	17 / 25 [j]	[R16]
	–	0.93 (± 0.62)	–	–	[P14]
	65 (5–195)	1.0 (0.08–3.1)	–	–	[N25]
	28.9	–	91.1	17.3	[B54]
	–	–	43.6	–	[W41]
Valvuloplasty	53 [k] (40–120)	–	56 [k]	–	[S15]
	–	–	44 [l]	–	[S15]
	31.8	–	162	29.3	[B54]
Lysis	21	–	–	–	[M8]
Embolization	25	-	180	25	[S14]
	37.4 (8.1–58)	-	121 (34–286)	–	[F5]
	(8.4–6.4) [m]	-	–	–	[N6]
	(17.5–90) [n]	-	–	–	[N6]
	23 [o] (1–75)	-	114 [o] (7–394)	–	[F6]
	–	(0.2–1.4) [p]	–	(6–43)	[B8]
	–	0.5 [q]	81.7 [q]	–	[V3]
	–	–	391 (93–918)	–	[B9]

Table 18 (continued)

Procedure	*Fluoroscopy time (min)*	*Localized dose to skin (Gy)*	*Dose-area product (Gy cm²)*	*Effective dose (mSv)*	*Ref.*
Embolization (continued)	21 [p] (6–54) 34.1 [p] (15.2–55.8) 43 [o] (31–74) 24.3 [m] (5–48) – – –	– 0.34 [p] (019–0.66) 0.62 [o] (0.13–1.34) 0.44 [m] – – –	122 [p] 105 [p] (57.2–201) 116 [o] (29–243) 79 [m] (55–100) – – 105 (352 max.)	10.6 [p] 10.5 [p] (5.7–20) 1.67 [o] (0.44–3.44) 15.9 [m] 20 [o] (± 14) adult 68 [o] (± 51) child. –	[M9] [M34,M36] [B17] [H27] [G12] [G12] [W32]
Biliary	– 7.1 (0.6–26.3) 30.4 (3.6–141) 34.2 (± 11.5) –	2.1 0.11 (0.01–0.37) – – –	68.9 (30–163) 43.1 (3.8–149) 20.1 (1.2–122) 150 (51–291) 43 (167)	– 6.9 (0.6–23.9) – 38.2 –	[V3] [M34,M36] [M35] [R17] [W32]
Stent (superior vena cava)	17 (± 9)	2 (max.)	42 (± 29)	5.8	[O9]

a Mean values of parameters (with range, standard deviation, or coefficient of variation in parentheses).
b Procedure carried out with laser.
c Total occlusion.
d Subtotal stenosis.
e No data available.
f Leg.
g Atrioventricular.
h Atrioventricular nodal reentry.
i Wolff–Parkinson–White.
j Values for males and females, respectively.
k Children (1–16 years).
l Infants (<1 year).
m Liver.
n Kidney.
o Neurological.
p Cerebral.
q Hepatic.

Table 19
Doses to patients from computed tomography

Country / area	*Year*	*Mean effective dose per procedure (mSv)*							
		Head	*Cervical spine*	*Chest*	*Abdomen*	*Liver*	*Kidneys*	*Pelvis*	*Lumbar spine*
Health-care level I									
Australia [T17]	1995	2.6	5.2	10.4	16.7	12.7	-	11.0	5.2
Finland [S67]	1994	1.3	-	5.1	11.6	-	-	-	5.0
Germany [B58]	1993	2.6	9 [b]	20.5	27.4	-	-	-	9 [b]
Japan [N16]	1994	-	-	4.6-10.8 [c]	6.7-13.3 [c]	-	-	-	-
Netherlands [V15]	1993	0.8-5.0 [a]	-	6-18	6-24 [a]	-	-	-	2-12 [a]
New Zealand [P5]	1992	1.8	3.3	8.9	9.7	6.5	7.6	6.9	4.7
Norway [O12]	1993	2.0	-	11.5	12.8	11.9	9.9	9.8	4.5
Sweden [S68]	1991	2.1	6	10 [d]	10 [d]	10 [d]	10 [d]	10 [d]	6 [b]
United Kingdom (Wales) [H33]	1994	1.6	1.5	9.7	12.0	10.3	9.1	9.8	3.3
Health-care level II									
Oman [G37]	1998	2.4	3.5	3.4	9.5	-	-	-	-

a Reported range for survey of 22 scanners.
b Published value for spine.
c Reported range for survey of 4 scanners.
d Published value for trunk.

Table 20
Patient dose [a] per procedure from chest radiography

Technique	*Conditions*	*Projection*	*Entrance surface dose (mGy)*	*Effective dose (mSv)*	*Ref.*
Film-screen	–	PA	0.168	–	[S77]
	–	PA	–	0.007–0.017	[S78]
	With lung filter	PA	–	0.008–0.011	[S78]
	With grid	PA	0.128	–	[C38]
	Without grid	PA	0.087	–	[C38]
	With air gap	PA	0.025	–	[C38]
	Asymmetric combination	PA	0.131	–	[C38]
	Twin combinations	PA	0.4	–	[M65]
Computed radiography	–	PA	0.68	0.10	[M4]
	–	LAT	1.70	0.15	[M4]
Beam equalization (AMBER)	–	PA	0.16	0.024	[M4]
	–	LAT	0.65	0.066	[M4]
Selenium drum	150 kV	PA	0.145	–	[L33]
	90 kV Standard dose	PA	0.16	–	[L33]
	90 kV Low dose	PA	0.07	–	[L33]
Digital Image Intensifier	–	PA	0.11	0.016	[M4]
	–	LAT	0.15	0.013	[M4]
100 mm film	–	PA	0.10	0.015	[M4]
	–	LAT	0.77	0.069	[M4]
Photofluorography	Survey of 80 units	–	5.8	0.36 (0.05–2.4)	[P26]
Mobile	–	PA	–	0.013	[S78]
	Intensive therapy unit	–	0.31–0.56	0.15	[L34]
	Intensive therapy unit	–	0.33 ± 0.11	–	[S79]
	Wards	–	0.2	–	[S79]

a Mean value, standard deviation or range.

Table 21
Frequencies of examinations and doses in dental radiology (1991-1996)
Data from UNSCEAR Survey of Medical Radiation Usage and Exposures unless otherwise indicated

Country / area	*Number of examinations [a] per 1,000 population*			*Effective dose per examination [b] (μSv)*		
	Intraoral	*Panoral*	*All*	*Intraoral*	*Panoral*	*All*
Health-care level I						
Australia	–	23	–	–	–	–
Bahrain	–	–	49	–	–	–
Belarus	75	6	81	80 (30–50%)	150 (30–50%)	–
Croatia	168	63	231	–	–	–
Cyprus	–	12	12	–	–	–
Czech Republic	–	–	193	–	–	100
Denmark	–	–	471	–	–	–
Ecuador	14	0.24	14	–	–	–
Finland	254	36	290	5 (1–24)	–	–
Germany	276	–	276	10 (1–1 000)	–	10 (1–1 000)
Hungary	–	–	41	–	–	–
Japan [c]	743	88	839	14	11	14
Kuwait	–	–	100	–	–	–
Lithuania	–	–	108	–	–	–
Luxembourg	438	31	469	–	–	–
Netherlands [d]	170 [d]	8 [d]	182 [d]	8 [d]	10	8 [d]
New Zealand [c]	–	–	–	5	26	–
Poland [S49]	70	3.4	74	–	–	–
Portugal [F11]	–	–	100	–	–	–
Romania	28	0	28	100 (± 70)	–	100 (± 70)
Russian Federation	–	–	96	–	–	36
Slovakia	77	17	94	–	–	–
Slovenia	46	9.8	55	–	–	–
Sweden	682	57	739	10	10	10
Switzerland	524	34	571	10 (± 10)	50 (± 20)	30 (± 30)
United Arab Emirates	7.8	7.6	15	–	–	–
United Kingdom	161	49	212	10 (3–19)	11	10
Average	365	47	309	13	12	16
Health-care level II						
Brazil	111	–	111	–	–	–
China	–	–	1.7	–	–	–
Jordan	3.0	0.1	3.1	–	–	–
Mexico	–	1.2	1.2	–	–	–
Oman	0	2.3	2.3	–	–	–
Turkey	–	–	31	–	–	–
Average	106	1.1	14	–	–	–
Health-care level III						
Ghana	–	–	0.25	–	–	–
Health-care level IV						
United Rep. of Tanzania	0.07	0	0.07	–	–	–

a Some values may represent numbers of films rather than complete examinations.
b Some doses may relate to individual films rather than complete examinations. Variations in parentheses (standard deviation, coefficient of variation or range).
c Data refer to individual films.
d These revised data were received by the Committee after completion of the global analysis.

Table 22
Doses to patients from dental x-ray examinations
Data from UNSCEAR Survey of Medical Radiation Usage and Exposures unless otherwise indicated

Country	*Year*	*Technique*	*Condition of measurement*	*Typical entrance surface dose [a] per exposure (mGy)*	
				Survey mean	*S.D. [b]*
Health-care level I					
Canada	1995	Intraoral	Survey of 56 units	2.5	(1.6–3.6)
Greece [Y11]	1997	Intraoral (50 kV)		6.5	4.9
		Intraoral (60 kV)		4.9	3.7
		Intraoral (65 kV)		3.1	1.2
		Intraoral (70 kV)		1.9	0.9
Denmark [H31]	1993	Intraoral (D speed film)	National survey	4.9	4.3
		Intraoral (E speed film)	National survey	3.2	3.6
United Arab Emirates	1997	Intraoral	4 units	2.77	(2.61–3.2)
		Intraoral	RVG filmless system	0.72	–
United Kingdom [N23]	1998	Intraoral (All)	Sample of 6344 measurements	3.3	(0.14–46)
		Intraoral (E speed film)	Sample of 1577 measurements	2.6	(0.14–21)
		Intraoral (45-55 kV)	Sample of 2175 measurements	5.0	(0.6–46)
		Intraoral (60-70 kV)	Sample of 3105 measurements	2.2	(0.2–9.6)
		Panoral	Sample of 387 measurements	57.4 mGy mm [c]	(2–328 mGy mm) [c]
United States	1993	Intraoral	NEXT programme	1.9	–
		Cephalometric	NEXT programme	0.21	–
Health-care level II					
Brazil	1996	Intraoral	Survey data for Paraná State	7.9	(0.9–61)

a Without backscatter.
b Dose range given in parentheses.
c Dose-width product [N23].

Table 23
Variation with technique of the typical effective dose from dental radiography
[N3]

Radiographic technique		*Effective dose (μSv)*
Two bitewing films	70 kV [a], 200 mm fsd [b], rectangular collimation, E speed film	2
	70 kV, 200 mm fsd, circular collimation, E speed film	4
	50-60 kV, 100 mm fsd, circular collimation, E speed film	8
	50-60 kV, 100 mm fsd, circular collimation, D speed film	16
Single panoral film	Rare-earth intensifying screens	7
	Calcium tungstate intensifying screens	14

a Applied potential.
b Focus to skin distance.

Table 24
Doses to patients from mammography
Data from UNSCEAR Survey of Medical Radiation Usage and Exposures unless otherwise indicated

Country	Year	Technique	Condition of measurement	Typical dose per film (mGy)			
				Entrance surface dose [a]		Dose to glandular tissue	
				Survey mean	S.D. [b]	Survey mean	S.D. [b]
Health-care level I							
Argentina [c] [I4]	1993	400 speed film/screen	Patient surveys	11.08 (pre)	–	–	–
				7.26 (post)	–	–	–
Australia [H48]	1996	Screening	Patient survey (2 units; 2051 films)	–	–	2.26	(0.4–7.2)
Belgium [P28]	1997	Screening	24 centres (4.5 cm phantom)	7.5	2.4	1.4	0.4
		Screening	24 centres (patient survey)	8.0	2.9	1.5	0.5
Canada	1994	-	Standard breast phantom	–	–	1.1	(0.36–4.68)
[F19]	1999	Screening	Survey in Ontario (phantom)	–	–	1.5	–
Finland [S16]	1993	Screening	4.5 cm Acrylic phantom	6.3	3.1	1.0	0.48
France [M7]	1991	Screening	Survey in Bas-Rhin (phantom)	15.2	–	–	–
	1993	Screening	Survey in Bas-Rhin (phantom)	8.5	–	–	–
Germany [K49]	1992	W anode	Patient survey (1678 women)	8.36	4.22	1.59	0.56
	1993	Mo/W anode	Patient survey (945 women)	11.0	5.05	2.07	0.66
Greece [F7]	1990	Grid	4 cm Acrylic phantom	8.5	(5–15)	–	–
		Non-grid	4 cm Acrylic phantom	5.2	(1–25)	–	–
Italy [M6]	1997	-	Tuscany region (phantom)	7.9	–	–	–
		-	Tuscany region (patients)	9.5	–	–	–
Japan [S81]	1994	Screening	4 cm compressed breast	–	–	1.80	–
New Zealand	1996	-	Average breast thickness	–	–	1.45	0.47
[B12]	1993	Screening	Patient survey in Otago (phantom)	–	–	–	(0.7–8.5)
Norway [O10]	1994	Non-grid	Standard phantom	–	–	–	(0.4–0.8)
		Grid	Standard phantom	–	–	–	(0.7–2.0)
Panama	1995	-	-	5.97	2.70	–	–
Slovenia	1996	-	Standard phantom	6.82	2.59	–	–
Spain [C40]	1997	Screening	4.5 cm Acrylic phantom	6.1	2.0	1.3	0.4
	1997	Screening	Patient survey	5.7	2.6	1.0	0.4
Sweden	1996	Screening	Standard breast phantom	–	–	1.5	(0.7–3.2)
United Arab	1998	Screening	Standard breast phantom	–	–	2.65	(2.48–2.81)
Emirates [d]		Clinical	Standard breast phantom	–	–	2.71	(2.66–2.76)
		Clinical [e]	Standard breast phantom	–	–	0.23	–
United Kingdom [Y12]	1991	Screening	Standard breast phantom	–	–	1.28	(0.6–2.6)
	1996	Screening	Standard breast phantom	–	–	1.36	(0.7–2.5)
[B66]	1995	Screening	Patient survey (4 633 women)	–	–	2.0 [f]	–
	1995	Screening	Patient survey (4 633 women)	–	–	1.6 [g]	–
United States [S82]	1992	-	Standard breast phantom	–	–	1.49	–
	1997	-	Standard breast phantom	–	–	1.60	–
[K43]	1999	-	Survey of 6 000 patients (phantom)	–	–	2.6	–
Health-care level II							
Iran (Islamic	1993	–	Patient surveys	5.45 (pre)	1.94	–	–
Republic of) [h] [I4]		–		4.27 (post)	–	–	–
Turkey	1997	-	Localized survey	3.29	0.23	–	–

a Entrance surface dose or entrance surface air kerma; backscatter factor is generally <1.1 for mammographic exposures.
b Dose range given in parentheses.
c Values represent surveys before and after the introduction of a programme of quality control; data from two hospitals.
d Diagnostic data from four units with grid and one without grid; screening data from two units.
e Without grid.
f Mediolateral oblique view (mean breast thickness 57 mm).
g Craniocaudal view (mean breast thickness 52 mm).
h Data from one hospital. Values represent surveys (with mean breast thickness of 3 cm) before and after the introduction of a programme of quality control.

Table 25
Estimates of mean absorbed dose to the uterus from x-ray examinations
[W30]

Examination	*Typical dose (mGy)*	*Reported range (mGy)*
Dental	– [a]	0.0003–0.001
Head / cervical spine	–	<0.005–0.03
Extremities	–	<0.005–0.18
Shoulder	–	<0.005–0.03
Thoracic spine	–	<0.10–0.55
Chest (radiography)	–	0.002–0.43
Chest (photofluorography)	–	0.009–0.40
Mammography	–	<0.1
Abdomen	2.5	0.25–19.0
Upper GI	1	0.05–12.0
Cholecystography / cholangiography	1	0.05–16.0
Lumbar spine	4	0.27–40.0
Lumbosacral spine	4	0.30–24.0
Urography	6	0.70–55.0
Urethrocystography	–	2.7–41.0
Barium enema	10	0.28–130
Hysterosalpingography	10	2.7–92
Pelvis	2	0.55–22.0
Hips and femur	3	0.73–14.0
Femur (distal)	–	0.01–0.50

a No data available.

Table 26
Provision for dual energy x-ray absorptiometry in various countries
[C10]

Health-care level	*Country*	*Scanners per million population*
I	Australia	3.4
	Austria	6.5
	Belgium	10.4
	Canada	2.3
	Cyprus	7.1
	Denmark	3.5
	Finland	3.4
	France	6.6
	Germany	6.8
	Greece	13.5
	Israel	2.6
	Japan	2.6
	Malta	2.5
	Netherlands	1.8
	Portugal	1.6
	Spain	3.5
	Switzerland	4.1
	United Kingdom	1.6
	United States	2.9
II	Chile	1.6

Table 27
Summary of entrance surface dose measurements from surveys of paediatric radiography in Europe (1989-1995)
[K4]

X-ray examination	*Entrance surface dose (μGy)*								
	Infant (10 months)			*5-year old*			*10-year old*		
	Median	*Minimum*	*Maximum*	*Median*	*Minimum*	*Maximum*	*Median*	*Minimum*	*Maximum*
Chest AP (1 kg newborn)	45	11	386	– [a]	–	–	–	–	–
Chest PA/AP	75	21	979	67	19	1 347	71	17	1 157
Chest AP (mobile)	90	34	718	68	29	333	91	29	760
Chest lateral	–	–	–	140	37	554	153	39	1 976
Skull PA/AP	930	152	4 514	967	242	4 626	1 036	130	5 210
Skull lateral	–	–	–	703	138	2 358	577	113	3 787
Pelvis AP (4 month)	260	18	1 369	–	–	–	–	–	–
Pelvis AP	–	–	–	485	86	2 785	812	89	4 167
Full spine PA/AP	867	107	4 351	–	–	–	–	–	–
Thoracic spine AP	–	–	–	–	–	–	887	204	4 312
Thoracic spine lateral	–	–	–	–	–	–	1 629	303	6 660
Lumbar spine AP	–	–	–	–	–	–	1 146	131	5 685
Lumbar spine lateral	–	–	–	–	–	–	2 427	249	23 465
Abdomen AP/PA	440	77	3 210	588	56	2 917	729	148	3 981

a No data available.

Table 28
Examples of reduced doses in paediatric radiography with attention to good technique
[C20]

Radiograph	*Age or weight*	*Entrance surface dose* [a] *(mGy)*	*Dose-area product (Gy cm²)*	*Effective dose (mSv)*
Chest - neonatal [b]	1 kg	0.01	–	0.02
	2 kg	0.02	–	0.04
	3 kg	0.03	–	0.07
Chest - AP/PA	0–1 month	0.02	0.002	≤0.01
	1–12 months	0.02	0.003	≤0.01
	1–4 years	0.03	0.005	≤0.01
	5–9 years	0.04	0.016	≤0.01
	10–15 years	0.05	0.029	≤0.01
Abdomen - AP	0–1 month	0.05	0.004	≤0.01
	1–12 months	0.05	0.009	≤0.01
	1–4 years [c]	0.09 / 0.16	0.017 / 0.030	0.02 / 0.04
	5–9 years	0.25	0.074	0.06
	10–15 years	0.66	0.36	0.13
Pelvis/hips - AP/Frog LAT	0–1 month	0.05	0.003	≤0.01
	1–12 months	0.07	0.005	≤0.01
	1–4 years [c]	0.08 / 0.22	0.011 / 0.068	≤0.01 / 0.03
	5–9 years	0.42	0.15	0.06
	10–15 years	1.13	0.29	0.17
Skull - AP	0–1 month	0.12	0.015	≤0.01
	1–12 months	0.15	0.022	≤0.01
	1–4 years	0.48	0.08	≤0.01
	5–9 years	0.73	0.11	≤0.01
	10–15 years	0.94	0.20	≤0.01
Skull - LAT	0–1 month	0.07	0.009	≤0.01
	1–12 months	0.09	0.014	≤0.01
	1–4 years	0.30	0.053	≤0.01
	5–9 years	0.36	0.060	≤0.01
	10–15 years	0.46	0.11	≤0.01

Table 28 (continued)

Lumbar spine - AP	0–1 month 1–12 months 1–4 years 5–9 years 10–15 years	0.07 0.19 0.37 0.98 1.75	0.006 0.010 0.048 0.23 0.54	≤0.01 0.02 0.05 0.14 0.22
Lumbar spine	0–1 month 1–12 months 1–4 years 5–9 years 10–15 years	0.08 0.14 0.70 1.52 8.46	0.006 0.012 0.10 0.30 2.22	≤0.01 ≤0.01 0.04 0.09 0.43
Full spine (scoliosis) - PA	0–1 month 1–12 months 1–4 years 5–9 years 10–15 years	– – 0.21 0.22 0.30	– – 0.069 0.070 0.095	– – – – –
Full spine (scoliosis) - LAT	0–1 month 1–12 months 1–4 years 5–9 years 10–15 years	– – 0.37 0.40 0.54	– – 0.086 0.12 0.14	– – – – –
Barium meal / barium swallow	< 1 years 1–5 years	– –	0.34 [d] (0.18–0.56) 0.60 [d] (0.36–0.94)	– –
Micturating cystourethrography (MCU)	< 1 years 1–4 years 5–10 years	– – –	0.26 [d] (0.06–0.62) 0.25 [d] (0.10–0.49) 0.45 [d] (0.29–0.60)	– – –

a With backscatter.
b Examinations conducted in a special care baby unit using mobile x-ray equipment. Data given by patient weight (kg).
c Dual dose data refer to small and large children, respectively.
d Mean and range from survey with screening times of 0.5–5.2 min and 3–10 films (100 mm format).

Table 29
Some reported annual individual and collective effective doses from diagnostic medical x-ray examinations [a]
Data from UNSCEAR Survey of Medical Radiation Usage and Exposures unless otherwise indicated

Country	*Effective dose (mSv)*		*Collective effective dose (man Sv)*	*Ref.*
	Per examination	*Per caput*		
Health-care level I				
Australia	1.3	0.8	13 000	[W34]
Bulgaria	1.28	0.75	6 400	-
Canada	1.05	0.94	26 200	[A15]
China, Taiwan Province	0.43	0.23	4 700	[L23]
Denmark	0.7	0.36	1 820	-
Finland	0.63	0.45	2 270	-
France	-	1.0	57 660	[S50]
Germany	1.5	1.9	153 360	-
Netherlands	1.0	0.6	9 000	-
Poland	1.2	0.8	32 300	-
Portugal	0.83	0.71	7 000	[F11]
Romania	1.35	0.61	13 800	-
Russian Federation	0.7	0.9	128 000	-
Sweden	1.2	0.68	6 000	-
Ukraine	0.83	0.50	26 250	[K18]
United States	0.5	0.5	130 000	-
Health-care level II				
Brazil [b]	0.26	0.09	-	-
China	0.57	0.08	91 600	[Z10]
Malaysia	0.28	0.05	1 000	[N26]

a Since, as discussed in Section I.C, many of these exposures are received by patients nearing the end of their lives and the doses are not distributed evenly amongst the population, these doses should not be used for the assessment of detriment. Some data may erroneously include dental examinations.

b Data for Paraná State (with a population of 9 million and a social and economic profile above the average for Brazil).

Table 30
Frequencies, effective doses and collective doses[a] assumed in global model for diagnostic practice with medical and dental x-ray examinations[b] (1991-1996)

Examination	*Number of examinations per 1,000 population*				*Effective dose per examination (mSv)*				*Annual collective dose (man Sv)*			
	Level I	*Level II*	*Levels III-IV*	*World*	*Level I*	*Level II*	*Levels III-IV*	*World*	*Level I*	*Level II*	*Levels III-IV*	*World*
Medical examinations												
Chest radiography	281	23	3.8	87	0.14	0.14	0.20	0.14	60 200	10 050	920	71 200
Chest photofluoroscopy	35	0.1	0.01	9.4	0.65	0.65	0.65	0.65	35 100	200	10	35 300
Chest fluoroscopy	12	63	0.01	37	1.1	1.1	1.1	1.1	20 900	214 000	10	234 700
Limbs and joints	166	19	4.8	55	0.06	0.06	0.1	0.06	15 200	3 600	600	19 400
Lumbar spine	48	4.4	0.92	15	1.8	1.8	2	1.8	132 000	24 200	2 200	159 000
Thoracic spine	13	1.2	0.42	4.1	1.4	1.4	1.5	1.4	27 600	5 000	770	33 400
Cervical spine	32	2.9	0.64	10	0.27	0.27	0.3	0.27	13 300	2 400	230	15 900
Pelvis and hip	35	2.8	1.5	11	0.83	0.83	1	0.83	44 300	7 200	1 800	53 300
Head	59	6.0	2.8	19	0.1	0.1	0.15	0.1	9 050	1 850	510	11 400
Abdomen	41	12	1.4	18	0.5	0.6	1	0.55	31 100	22 600	1 700	55 400
Upper GI tract	42	3.2	0.85	13	3.6	4	4	3.7	231 000	39 500	4 080	274 000
Lower GI tract	8.7	1.7	1.2	3.4	6.4	6.4	6.4	6.4	85 100	32 500	9 260	127 000
Cholecystography	3.1	0.19	0.07	0.94	2	2	2	2	9 500	1 200	170	10 900
Urography	12	0.97	0.59	3.8	3.7	3.9	4	3.7	66 800	11 700	2 860	81 300
Mammography	25	0.58	0.01	7.0	0.5	0.5	0.5	0.5	19 400	900	10	20 300
CT	57	1.5	0.07	16	8.8	5	5	8.6	762 000	22 400	430	785 000
Angiography	7.6	0.10	0.01	2.1	12	12	12	12	140 000	3 600	100	143 000
Interventiona1 procedures	3.0	0.10	0.01	0.84	20	20	20	20	91 800	6 000	170	98 000
Total	920	150	20	330	-	-	-	-	1 875 000	425 000	27 000	2 330 000
Average effective dose per medical x-ray examination (mSv)					1.3	0.9	1.1	1.2				
Average effective dose per caput from medical x-ray examinations (mSv)									1.2	0.14	0.02	0.40
Dental examinations												
Total	310	14	0.2	90	-	-	-	-	9 500	4 300	24	14 000
Average effective dose per dental x-ray examination (mSv)					0.02	0.1	0.1	0.03				
Average effective dose per caput from dental x-ray examinations (mSv)									0.01	0.001	0.00002	0.002

a Since, as discussed in Section I.C, many of these exposures are received by patients nearing the end of their lives and the doses are not distributed evenly amongst the population, these doses should not be used for the assessment of detriment.

b Rounded estimates based on self-consistent frequency data from a selected sample of representative countries and typical (or assumed) doses from the UNSCEAR Survey of Medical Radiation Usage and Exposures.

Table 31
Contributions to frequency and collective dose from the various types of diagnostic medical x-ray examinations assumed for global model (1991-1996)

Examination	*Contribution (%)*			
	Level I	*Level II*	*Levels III-IV*	*World*
Contribution to total annual frequency				
Chest radiography	31	16	19	27
Chest photofluorography	4	0.1	< 0.1	3
Chest fluoroscopy	1	42	< 0.1	11
Limbs and joints	18	13	24	17
Lumbar spine	5	3	5	5
Thoracic spine	1	0.8	2	1
Cervical spine	4	2	3	3
Pelvis and hip	4	2	7	3
Head	6	4	14	6
Abdomen	4	8	7	5
Upper GI tract	5	2	4	4
Lower GI tract	0.9	1	6	1
Cholecystography	0.3	0.1	0.4	0.3
Urography	1	0.6	3	1
Mammography	3	0.4	< 0.1	2
CT	6	1.0	0.4	5
Angiography	0.8	0.1	< 0.1	0.6
Interventional procedures	0.3	0.1	<0.1	0.3
Other	4	4	4	4
All	100	100	100	100
Contribution to total annual collective dose				
Chest radiography	3	2	3	3
Chest photofluorography	2	< 0.1	< 0.1	2
Chest fluoroscopy	1	50	< 0.1	10
Limbs and joints	0.8	0.8	2	0.8
Lumbar spine	7	6	8	7
Thoracic spine	1	1	3	1
Cervical spine	0.7	0.6	0.9	0.7
Pelvis and hip	2	2	7	2
Head	0.5	0.4	2	0.5
Abdomen	2	5	6	2
Upper GI tract	12	9	15	12
Lower GI tract	5	8	34	5
Cholecystography	0.5	0.3	0.6	0.5
Urography	4	3	11	3
Mammography	1	0.2	< 0.1	0.9
CT	41	5	2	34
Angiography	7	0.8	0.4	6
Interventional procedures	5	1	0.6	4
Other	4	4	4	4
All	100	100	100	100

Table 32
Temporal trends in the annual frequency of diagnostic medical x-ray examinations per 1,000 population [a]
Data from UNSCEAR Surveys of Medical Radiation Usage and Exposures unless otherwise indicated.

Country / area	*1970-1979*	*1980-1984*	*1985-1990*	*1991-1996*
Health-care level I				
Australia	490	– [b]	560	565
Bahrain	–	–	–	202
Belarus	–	–	–	726
Belgium	–	–	1290	–
Bulgaria	(980)	(1100)	(800)	589
Canada	860	1020	1050	892
China, Taiwan Province	–	–	–	480
Croatia	–	–	–	903
Cuba	–	140	620	–
Cyprus	–	–	–	937
Czechoslovakia	1110	1050	920	–
Czech Republic	–	–	–	883
Denmark	–	–	510	510
Ecuador	(26)	–	(53)	151
Estonia	–	–	–	1000
Finland	1080	–	870	704
France	–	840	990	–
Germany	900	–	1050	1254
Hungary	–	–	–	475
Italy	–	740	–	–
Japan	830	–	1160	1477
Kuwait	–	–	720	896
Lithuania	–	–	–	886
Luxembourg	–	–	810	1046
Malta	100	–	320	–
Netherlands	570	550	530	598
New Zealand	610	710	640	–
Norway	–	640	620	708
Panama	–	–	–	300
Poland [S49]	900	–	540	641
Portugal	–	–	700	850
Qatar	–	–	–	495
Romania	790	600	470	450
Russian Federation	(1340)	(1560)	(1260)	1151
Slovakia	–	–	–	800
Slovenia	–	–	–	348
South Africa	–	–	–	180
Spain	–	–	570	–
Sweden	590	–	520	568
Switzerland	1040	1040	–	750
Ukraine [K18]	–	–	948	600
United Arab Emirates	–	–	–	378
United Kingdom	420	460	–	489
United States	–	790	800	962
Average	820	810	890	920
Health-care level II				
Antigua and Barbuda	–	–	–	271
Barbados	–	–	160	174
Brazil	–	180	93	261
Chile	–	170	–	–
China	–	110	150	173 [c]
Colombia	–	210	–	–
Costa Rica	–	270	–	–
Dominica	–	–	(180)	185
Dominican Republic	–	20	–	–
Grenada	–	–	–	158
India	(23)	–	110	–
Iran (Islamic Rep. of)	–	180	–	–
Jordan	–	–	–	45
Malaysia	–	–	–	183
Mexico	–	70	–	306
Nicaragua	–	57	13	–
Oman	–	–	–	269
Peru	–	–	15	–

Table 32 (continued)

Country / area	*1970-1979*	*1980-1984*	*1985-1990*	*1991-1996*
Saint Kitts and Nevis	–	–	–	203
Saint Lucia	–	–	(130)	134
Saint Vincent and the Grenadines	–	–	–	147
Turkey	–	–	524	98
Average	26	140	120	154
Health-care level III				
Belize	–	–	83	–
Cape Verde	–	–	69	–
Ghana	22	–	–	7
Liberia	80	–	–	–
Madagascar	–	–	–	11
Morocco	–	–	–	8
Myanmar	–	–	10	–
Philippines	–	–	110	–
Sri Lanka	21	–	–	–
Sudan	–	–	53	37
Thailand	50	75	79	–
Vanuatu	–	–	100	–
Average	23	75	67	17
Health-care level IV				
Cote d'Ivoire	40	–	–	–
Kenya	36	–	–	–
Nigeria	25	–	–	–
Rwanda	8.0	–	8.8	–
Tanzania	–	–	–	29
Average	27	–	8.8	29

a Dental x-ray examinations not included.
b No data available.
c These revised data were received by the Committee after completion of the global analysis.

The entries in this Table are qualified as follows:

Bulgaria: Historical data were not included in previous analyses.
Czechoslovakia: Historical data.
Dominica: Categorized in health-care level III in previous analysis.
Ecuador: Categorized in health-care level II in previous analyses.
Germany: Data for 1970–1979 and 1985–1990 represent combined historical data for German Democratic Republic and Federal Republic of Germany.
India: Categorized in health-care level III for period 1970–1979.
Russian Federation : Historical data were not included in previous analyses.
Saint Lucia: Categorized in health-care level III in previous analysis.

Table 33
Temporal trends in the average annual number of diagnostic x-ray examinations per 1,000 population
Data from UNSCEAR Surveys of Medical Radiation Usage and Exposures

Examination	*Period*	*Average annual number of examinations per 1,000 population* [a]		
		Health-care level I	*Health-care level II*	*Health-care levels III-IV*
Chest	1970–1979	588	11	18
	1980–1984	588	80	45
	1985–1990	527(52%)	118 (73%)	51 (70%)
	1991–1996	368 (39%)	89 (58%)	4.9 (21%)
Limbs and joints	1970–1979	87	3.3	3.2
	1980–1984	151	7.8	7.4
	1985–1990	137 (14%)	15 (8.9%)	6.2 (8.8%)
	1991–1996	212 (21%)	20 (13%)	6.8 (24%)
Spine	1970–1979	25	1.7	1.9
	1980–1984	58	1.7	5
	1985–1990	61 (6.1%)	3.9 (2.4%)	2 (2.8%)
	1991–1996	100 (11%)	8.9 (5.8%)	3.6 (11%)
Pelvis and hip	1970–1979	22	2.7	0.57
	1980–1984	31	0.44	1.5
	1985–1990	38 (3.7%)	3.4 (2.1%)	2 (2.8%)
	1991–1996	36 (4.0%)	14 (5.9%)	1.7 (6.6%)
Head	1970–1979	13	2.3	1.8
	1980–1984	37	1.5	3.4
	1985–1990	46 (4.5%)	5.8 (3.5%)	3.7 (5.2%)
	1991–1996	60 (6.5%)	30 (13%)	3.3 (14%)
Abdomen	1970–1979	15	4.1	4.7
	1980–1984	22	14	6.5
	1985–1990	36 (3.6%)	7.9 (4.8%)	3.4 (4.7%)
	1991–1996	41 (4.6%)	13 (8.2%)	2.0 (7.1%)
GI tract	1970–1979	73	0.92	1.6
	1980–1984	51	2.7	2.6
	1985–1990	72 (7.1%)	5 (3.1%)	1.8 (2.5%)
	1991–1996	60 (6.4%)	5.1 (3.3%)	2.9 (10%)
Cholecystography and urography	1970–1979	19	0.48	1.2
	1980–1984	28	0.35	2.6
	1985–1990	26 (2.6%)	2.7 (1.6%)	2.2 (3.1%)
	1991–1996	15 (1.6%)	5.6 (2.4%)	0.9 (3.3%)
Mammography	1970–1979	5.2	0.07	–
	1980–1984	4.6	0.09	–
	1985–1990	14 (1.4%)	0.57 (0.3%)	(0.1%)
	1991–1996	25 (2.9%)	2.7 (1.2%)	0.01 (0.1%)
CT	1970–1979	6.1	0	0.14
	1980–1984	11	0	1.3
	1985–1990	44 (4.4%)	0.42 (0.3%)	0.42 (0.6%)
	1991–1996	48 (6.4%)	6.7 (2.9%)	0.14 (0.8%)
Angiography	1970–1979	1.6	0	0.3
	1980–1984	5.7	0	0.3
	1985–1990	7.1 (0.7%)	0.27 (0.2%)	0.11 (0.2%)
	1991–1996	6.8 (0.8%)	0.48 (0.2%)	0
Interventional procedures	1991–1996	2.7 (0.4%)	0.94 (0.4%)	0
Pelvimetry	1991–1996	0.6 (0.1%)	1.7 (0.8%)	0.3 (1.0%)
Total	1970–1979	814	26	29
	1980–1984	804	141	75
	1985–1990	887 (100%)	124 (100%)	64 (100%)
	1991–1996	920 (100%)	154 (100%)	20 (100%)

a Overall averages calculated from national data as the total number of examinations divided by the total population for each examination category. The figures in parentheses indicate an average percentage contribution of each examination category to total frequency, calculated on a similar basis. Data for 1991–1996 from Tables 12 and 13; since the total population is not the same for each examination category due to the lack of comprehensive national data for all countries listed in the tables, these average numbers can not be expected to be additive.

Table 34
Temporal trends in annual frequency of diagnostic dental x-ray examinations per 1,000 population
Data from UNSCEAR Surveys of Medical Radiation Usage and Exposures

Country	*1970-1979*	*1980-1984*	*1985-1990*	*1991-1996*
Health-care level I				
Australia	80	–	–	–
Bahrain	–	–	–	49
Belarus	–	–	–	81
Belgium	–	–	288	–
Croatia	–	–	–	231
Cyprus	–	–	–	12
Czechoslovakia [a]	72	86	85	–
Czech Republic	–	–	–	193
Denmark	–	–	471	471
Ecuador [b]	(1.5)	(4.4)	(6.2)	14
Finland	–	–	223	290
France	–	540	–	–
Germany [c]	–	–	264	276
Hungary	–	–	–	41
Italy	–	119	–	–
Japan	831	834	783	839
Kuwait	–	–	219	100
Lithuania	–	–	–	108
Luxembourg	–	–	186	469
Malta	3	6.2	8.2	–
Netherlands	(75) [e]	(200) [e]	(205) [e]	182 [e]
New Zealand	321	–	275	–
Norway	641	805	833	–
Poland [S49]	–	–	32	74
Portugal	–	–	86	100
Romania	20	32	42	28
Russian Federation [d]	–	(74)	(82)	96
Slovakia	–	–	–	94
Slovenia	–	–	–	55
Spain	–	–	232	–
Sweden	433	841	832	739
Switzerland	296	325	–	571
United Arab Emirates	–	–	–	15
United Kingdom	112	165	–	212
United States	350	456	402	–
Average	320	390	350	310
Health–care level II				
Brazil	–	–	4.7	111
Chile	–	3.9	–	–
China	–	0.8	2.1	1.7
Jordan	–	–	–	3.1
Mexico	–	–	–	1.2
Oman	–	–	–	2.3
Tunisia	–	–	1.3	–
Turkey	–	–	–	31
Average	–	0.8	2.5	14
Health–care level III				
Egypt	0.7	–	–	–
Ghana	–	–	–	0.3
Myanmar	–	–	1.6	–
Sri Lanka	0.8	–	–	–
Thailand	1.4	2.3	2.1	–
Average	–	0.8	1.7	0.3

Table 34 (continued)

Health–care level IV				
United Rep. of Tanzania	–	–	–	0.1
Average	–	–	–	0.1

a Historical data.
b Categorized in health-care level II in previous analyses.
c Data for 1985–1990 represent historical data for Federal Republic of Germany.
d Historical data were not included in previous analyses.
e These revised data were received by the Committee after completion of the global analysis.

Table 35
Trends in average effective doses from diagnostic medical x-ray examinations
Data from UNSCEAR Surveys of Medical Radiation Usage and Exposures

Examination	*Average [a] effective dose per examination (mSv)*				
	Health-care level I			*Health-care level II*	
	1970–1979	*1980–1990*	*1991–1996*	*1980–1990*	*1991–1996*
Chest radiography	0.25	0.14	0.14	0.04	0.05
Chest photofluoroscopy	0.52	0.52	0.65	–	–
Chest fluoroscopy	0.72	0.98	1.1	0.29	–
Limbs and joints	0.02	0.06	0.06	0.04	0.04
Lumbar spine	2.2	1.7	1.8	2.6	1.0
Pelvis and hip	2.1	1.2	0.83	2.0	0.74
Head	0.50	0.16	0.07	0.13	0.04
Abdomen	1.9	1.1	0.53	0.22	0.62
Upper GI tract	8.9	7.2	3.6	1.6	6.0
Lower GI tract	9.8	4.1	6.4	5.0	6.0
Cholecystography	1.9	1.5	2.3	1.6	1.5
Urography	3.0	3.1	3.7	1.7	3.9
Mammography	1.8	1.0	0.51	–	0.1
CT	1.3	4.3	8.8	–	4.9
Angiography	9.2	6.8	12	–	6.8
PTCA	–	–	22	–	–

a Frequency-weighted average of national values from survey data. Values for 1991–1996 from Table 15.

Table 36
Estimated doses to the world population from diagnostic medical and dental x-ray examinations [a]
1991–1996

Health-care level	*Population (millions)*	*Annual per caput effective dose (mSv)*		*Annual collective effective dose (man Sv)*	
		Medical	*Dental*	*Medical*	*Dental*
I	1 530	1.2	0.01	1 875 000	9 500
II	3 070	0.14	0.001	425 000	4 300
III	640	0.02	< 0.0001	14 000	13
IV	565	0.02	< 0.0001	13 000	11
World	5 800	0.4	0.002	2 330 000	14 000

a Since, as discussed in Section I.C, many of these exposures are received by patients nearing the end of their lives and the doses are not distributed evenly amongst the population, these doses should not be used for the assessment of detriment.

Table 37
Chronology of key technical advances in diagnostic nuclear medicine

Date	*Development*
1896	Discovery of natural radioactivity (Becquerel)
1920s	Biological tracer studies with radionuclides in plants and animals (Hevesey)
1930s	First cyclotron; production of artificial radioactivity (Fermi)
1940s	Controlled uranium fission; early clinical nuclear medicine with radioiodine; first artificial radioactive element named (^{99m}Tc)
1950s	Invention of rectilinear scanner (Cassen); invention of gamma camera (Anger)
1960s	Invention of ^{99m}Tc generator; early development of single-photon computed tomography (SPECT)
1970s	Increased use of computers; early development of positron emission tomography (PET)
1980s	Growth in SPECT
1990s	Growth in PET; more specific radiopharmaceuticals

Table 38
Annual numbers of diagnostic nuclear medicine procedures per 1,000 population by broad category and radionuclide (1991-1996)
Data from UNSCEAR Survey of Medical Radiation Usage and Exposures unless otherwise indicated

PART A

Country /area	*Bone (^{99m}Tc)*	*Cardiovascular*			*Lung perfusion (^{99m}Tc)*	*Lung ventilation*				*Thyroid scan*		
	Total	*^{99m}Tc*	*^{201}Tl*	*Total*	*Total*	*^{99m}Tc*	*^{81m}Kr*	*^{133}Xe*	*Total*	*^{99m}Tc*	*^{131}I / ^{123}I*	*Total*
Health-care level I												
Argentina	3.38	1.12	1.88	3.01	0.32	0.26	0	0	0.26	0.65	1.09	1.74
Belarus	0.23	–	–	–	–	–	–	–	–	0.012	0	0.012
Bulgaria	0.068	–	–	0.065	0.047	0.014	0	0	0.014	–	–	1.23
Canada	22.0	–	–	30.4	0.17	–	–	–	0.94	–	–	2.79
Cayman Islands	0	0	0	0	0	0	0	0	0	0	0	0
China, Taiwan Province [L6]	1.55	0.55	0.43	0.98	0.14	–	–	–	–	0.31	0	0.31
Croatia	0.53	0.033	0.23	0.27	0.066	0.0063	0	0	0.0063	0.47	0.071	0.54
Cyprus	1.83	0.40	1.42	1.82	0.12	0	0	0	0	1.33	0.065	1.39
Czech Republic	5.14	–	–	2.43	2.67	0.40	0	0	0.40	–	–	2.60
Denmark	2.91	1.29	0	1.29	0.90	0.024	0.34	0.18	0.54	2.05	0	2.05
Ecuador	0.25	0.057	0	0.057	0.029	0.015	0	0	0.015	0	0.21	0.21
Finland	3.86	0.90	0.34	1.25	1.18	0.22	0	0.002	0.22	0.11	0.051	0.17
Germany	8.96	–	–	2.82	2.58	–	–	–	–	17.2	0	17.2
Hungary	[3.93]	–	–	1.00	[1.05]	–	–	–	0.087	–	–	4.08
Ireland	2.74	0.33	0	0.33	0.66	0.15	0	0	0.15	0.047	0	0.047
Italy	3.68	0.83	0.67	1.50	0.44	0.063	0	0	0.063	2.40	0.11	2.51
Japan	2.74	0.44	0.39	0.84	0.27	–	–	–	–	0.36	0.58	0.94
Kuwait	0.90	2.55	0	2.55	0.27	–	–	–	–	3.95	0	3.95
Lithuania	0.33	0.013	0	0.013	0.025	0	0	0	0	0	1.65	1.65
Netherlands	6.12	–	–	3.12	1.10	–	–	–	1.14	–	–	0.84
New Zealand [L28]	4.10	0.60	0.007	0.61	0.75	0.40	0	0.17	0.57	0.62	0.041	0.66
Panama	0.18	0.20	0	0.20	0.19	0.22	0	0	0.22	1.73	0	1.73
Qatar	1.18	0.97	0	0.97	0.17	–	–	–	–	0.58	0	0.58
Romania	0.37	–	–	–	0.032	–	–	–	–	0.14	0.69	0.82
Slovakia	2.69	–	–	0.24	1.54	–	–	–	–	–	–	2.50
Slovenia	2.00	1.34	0.016	1.35	0.70	0.042	0	0.41	0.45	2.33	0.19	2.52
Sweden	3.84	0.68	0.40	1.08	1.48	0.60	0	0	0.60	1.01	0.21	1.22
Switzerland	4.09	–	–	0.54	1.30	0	0	–	0.61	–	–	1.44
United Arab Emirates	1.93	0.86	0.25	1.11	0.17	0.020	0	0	0.020	0.95	0	0.95
United States [I23]	7.72	–	–	4.05	5.08	–	–	–	–	–	–	–
Average	5.85	–	–	3.57	2.33	–	–	–	0.35	–	–	4.04

Table 38 (continued)

Country /area	Bone (^{99m}Tc)	Cardiovascular			Lung perfusion (^{99m}Tc)	Lung ventilation				Thyroid scan		
	Total	^{99m}Tc	^{201}Tl	Total	Total	^{99m}Tc	^{81m}Kr	^{133}Xe	Total	^{99m}Tc	^{131}I / ^{123}I	Total
Health-care level II												
Jordan	0.34	0.0066	0.004	0.011	0.008	0.0049	0	0	0.0049	–	–	0.73
Mexico	0.16	0.32	0	0.32	0.023	0.015	0	0	0.015	–	–	0.13
Oman	[0.17]	0	0	0	[0.020]	–	–	–	0.0009	–	–	0.043
Pakistan	0.071	0.0069	0	0.0069	0.0030	0	0	0	0	0.22	0	0.22
Peru	0.41	0.0068	0	0.0068	0.0085	–	–	–	0.0034	0.073	0.026	0.099
Tunisia	[0.033]	–	–	0.020	[0.056]	0	0	0	0	–	–	0.56
Turkey	0.49	–	–	0.30	0.038	0.023	0	0	0.023	0.53	0	0.53
Average	0.20	–	–	0.15	0.017	–	–	–	0.0089	–	–	0.26
Health-care level III												
Ghana [A16]	0.0022	–	–	–	–	–	–	–	–	0.024	0	0.024
Morocco	0.13	–	–	0.045	0.019	0	0	0	0	0.37	0	0.37
Sudan	0.011	0	0	0	0	0	0	0	0	0.046	0	0.046
Average	0.054	–	–	0.023	0.0095	–	–	–	0	–	–	0.16
Health-care level IV												
Ethiopia	0.0001	0	0	0	0.0001	0	0	0	0	0	0.0048	0.0048
Tanzania	0.0043	0	0	0	0.00007	0	0	0	0	0	0	0
Average	0.0014	–	–	0	0.0001	–	–	–	0	–	–	0.0033

PART B

Country / area	Thyroid uptake			Renal			Liver / spleen (^{99m}Tc)	Brain			Total of all nuclear medicine examinations
	^{131}I	^{123}I/^{125}I	Total	^{99m}Tc	^{131}I / ^{123}I	Total	Total	^{99m}Tc	Other	Total	
Health-care level I											
Argentina	1.19	0	1.24	0.79	0.03	0.82	0.13	0.22	0	0.22	11
Australia [C7]	–	–	–	–	–	–	–	–	–	–	12
Belarus	0.0041	0	0.0041	0.17	0	0.17	0.0020	0.0020	0	0.0020	0.48
Bulgaria	0	1.48	1.48	0.22	0	0.22	0.057	0.052	0	0.052	3.26

Table 38 (continued)

Country / area	*Thyroid uptake*			*Renal*			*Liver / spleen (^{99m}Tc)*	*Brain*			*Total of all nuclear medicine examinations*
	^{131}I	*$^{123}I/^{125}I$*	*Total*	*^{99m}Tc*	*^{131}I / ^{123}I*	*Total*	*Total*	*^{99m}Tc*	*Other*	*Total*	
Canada	–	–	2.95	1.63	0	1.63	0.59	1.54	0	1.54	64.6
Cayman Islands	0	0	0	0	0	0	0	0	0	0	0
China, Taiwan Province [L6]	–	–	0.35	0.29	0	0.29	1.33	0.65	0	0.65	6.63
Croatia	0.037	0	0.037	0.64	0	0.64	0.057	0.13	0	0.13	2.38
Cyprus	0.015	0	0.0015	1.07	0	1.07	0.020	0	0	0	6.65
Czech Republic	1.00	0	1.00	8.15	0	8.15	1.15	2.17	0	2.17	28.3
Denmark	0.31	0	0.31	3.44	0	3.44	0.018	0.17	0.17 (^{133}Xe)	0.34	15.2
Ecuador	0.17	0	0.17	0.029	0	0.029	0.021	0.0017	0	0.0017	0.79
Estonia [S29]	–	–	–	–	–	–	–	–	–	–	8.00
Finland	0.055	0.035	0.090	1.54	0.12	1.66	0.013	0.24	0.044 (^{123}I)	0.28	9.95
Germany	–	–	–	–	–	1.60	0.037	0.49	0	0.49	34.1
Hungary	–	–	0.68	–	–	2.54	[0.39]	–	–	0.34	15.3
Ireland	–	–	0.10	1.50	0	1.50	0.023	0.010	0	0.010	6.15
Italy	0.26	0	0.26	1.07	0.29	1.35	0.36	0.35	0	0.35	11.0
Japan	–	–	–	0.40	–	0.69	0.61	0.53	–	1.24	11.7
Kuwait	2.07	0	2.07	0.97	0	0.97	0.075	0.045	0	0.045	12.7
Lithuania	1.66	0	1.66	1.11	0	1.11	0.13	–	–	0.0013	10.6
Luxembourg	–	–	–	–	–	–	–	–	–	–	52.2
Netherlands	–	–	0.48	1.19	0	1.19	0.094	–	–	0.25	16.0
New Zealand [L28]	0.022	0	0.022	0.79	0	0.85	0.086	0.25	0	0.25	8.35
Panama	0.38	0	0.38	0.25	0	0.25	0.17	0.13	0	0.13	3.45
Portugal [F11]	–	–	–	–	–	–	–	–	–	–	4.00
Qatar	–	–	–	1.39	0	1.39	0.065	0	0	0	4.73
Romania	0.62	0	0.62	0.072	0.21	0.28	0.73	0.11	0	0.11	3.02
Russian Federation	–	–	–	–	–	–	–	–	–	–	12.6
Slovakia	–	0	0.0051	–	–	0.88	0.62	0.044	0	0.044	9.37
Slovenia	0.28	–	0.38	1.45	0	1.45	0.17	0.44	–	0.47	11.2
Sweden	0.52	0	0.52	0.43	0	0.43	0.077	0.055	0.039 (^{11}C)	0.093	13.6
Switzerland	–	–	–	–	–	0.39	0.049	–	–	0.17	9.51
Ukraine [K18]	–	–	–	–	–	–	–	–	–	–	5.00
United Arab Emirates	0	0	0.95	1.38	0	1.38	0.097	0.044	0	0.044	7.25
United Kingdom [E11]	–	–	–	–	–	–	–	–	–	–	8.21
United States [I23]	–	–	–	–	–	1.01	6.83	–	–	3.46	31.5
Average	–	–	0.80	–	–	1.11	2.60	–	–	1.62	18.8

Table 38 (continued)

Country / area	*Thyroid uptake*			*Renal*			*Liver / spleen (^{99m}Tc)*	*Brain*			*Total of all nuclear medicine examinations*
	^{131}I	*$^{123}I/^{125}I$*	*Total*	*^{99m}Tc*	*^{131}I / ^{123}I*	*Total*	*Total*	*^{99m}Tc*	*Other*	*Total*	
Health-care level II											
Antigua and Barbuda [B43]	–	–	–	–	–	–	–	–	–	–	0
Brazil	–	–	–	–	–	–	–	–	–	–	1.11
Dominica [B43]	–	–	–	–	–	–	–	–	–	–	0
Grenada [B43]	–	–	–	–	–	–	–	–	–	–	0
Iran (Islamic Rep of [M10]	–	–	–	–	–	–	–	–	–	–	1.89
Jordan	0.18	0	0.18	0.18	0	0.18	0.040	–	–	–	1.56
Mexico	0.022	0	0.022	0.16	0	0.16	0.093	0.075	0	0.075	1.06
Oman	–	–	0.051	–	–	0.22	[0.0035]	0	0	0	0.64
Pakistan	0	0	0.020	0.064	0	0.064	0.056	0.032	0	0.032	0.55
Peru	0.020	0	0.020	0.015	0	0.015	0.017	0.0034	0	0.0034	0.58
Saint Kitts and Nevis [B43]	–	–	–	–	–	–	–	–	–	–	0
Saint Lucia [B43]	–	–	–	–	–	–	–	–	–	–	0
Saint Vincent and the Grenadines [B43]	–	–	–	–	–	–	–	–	–	–	0
Tunisia	–	–	0.056	–	–	0.056	0	0	0	0	0.79
Turkey	–	–	–	0.32	0	0.32	0.14	0.037	0	0.037	2.07
Average	–	–	0.025	–	–	0.14	0.078	–	–	0.042	1.13
Health-care level III											
Ghana [A16]	–	–	–	0.0007	0	0.0007	0.0009	0.027	0	0.027	0.054
Morocco	0	0	0	0.038	0	0.038	0.0067	0	0	0	0.62
Sudan	0	–	0	0.014	0	0.014	0.0046	0.0092	0	0.0092	0.085
Average	–	–	0	–	–	0.019	0.0045	–	–	0.010	0.28
Health-care level IV											
Ethiopia	0.048	0	0.0048	0.0003	0	0.0003	0.0003	0.0038	0	0.0038	0.014
United Rep. of Tanzania	0	0	0.012	0.0061	0	0.0061	0	0.0008	0	0.0008	0.024
Average	–	–	0.0072	–	–	0.0021	0.0002	–	–	0.0028	0.017

Table 38 (continued)

The entries in this Table are qualified as follows:

Argentina: On the basis of data from a sample of 25% of nuclear medicine centres. Total shown for lung perfusion includes use of ^{67}Ga (frequency of 0.0017). Total shown for thyroid uptake includes use of ^{99m}Tc (frequency of 0.056). Total shown for bone scan includes use of ^{67}Ga (frequency of 0.034).
Brazil: Survey data for Paraná State (with a population of 9 million and a social and economic profile above the average for Brazil).
Canada: On the basis of data from Ontario (representing about 37% of population).
Cyprus: Survey data relating to 90% of population.
Finland: Total shown for lung perfusion scans includes use of ^{133}Xe (frequency of 0.002).
Ghana: Data for thyroid scan represent total of all thyroid studies.
Japan: Total frequency for bone scans is 2.77; total frequency for lung perfusion scans is 0.45.
Lithuania: Data from Vilnius Oncology Centre.
New Zealand: Total shown for renal scans includes use of ^{51}Cr (frequency of 0.064).
Peru: Survey data from IPEN (Centre of Nuclear Medicine, serving population of about 5 million).
Romania: Survey data relating to population base of about 4.5 million. Total for liver/spleen is 0.79 (includes use of ^{198}Au with frequency of 0.065).
Slovakia: Survey data relating to population base of about 2 million. Total for thyroid uptake includes use of ^{99m}Tc (frequency of 0.096).
Slovenia: Survey data relating to population base of about 1.8 million. Total frequency for lung perfusion is 0.82; total for thyroid uptake includes use of ^{99m}Tc (with frequency of 0.096).
Switzerland: Total for lung ventilation refers to use of ^{133}Xe and ^{127}Xe. Data for thyroid scans include uptake studies.
Turkey: On the basis of data from Hacettepe University Hospital.
United Arab Emirates: Thyroid uptake done simultaneously with thyroid scan using a single dose of ^{99m}Tc.
United Republic of Tanzania: Total shown for thyroid uptake refers to use of ^{99m}Tc.
Hungary, Oman, Tunisia: No information available on radionuclides used.

Table 39
Percentage contributions by types of procedure to annual total numbers of diagnostic nuclear medicine procedures (1991-1996)
Based on data and qualifications from Table 38

Country / area	*Bone*	*Cardiovascular*	*Lung perfusion*	*Lung ventilation*	*Thyroid scan*	*Thyroid uptake*	*Renal*	*Liver/spleen*	*Brain*	*Total of all procedures*
Health-care level I										
Argentina	30	27	2.9	2.3	16	11	7.4	1.2	1.9	100
Belarus	48	–	–	–	2.4	0.8	35	0.4	0.4	100
Bulgaria	2.1	2.0	1.4	0.4	38	45	6.8	1.7	1.6	100
Canada	34	47	0.3	1.5	4.3	4.6	2.5	0.9	2.4	100
China, Taiwan Prov.	23	15	2.1	–	4.7	5.3	4.4	20	9.8	100
Croatia	22	11	2.8	0.3	23	1.5	27	2.4	5.3	100
Cyprus	27	27	1.8	0	21	0.02	16	0.3	0	100
Czech Republic	18	8.6	9.5	1.4	9.2	3.5	29	4.1	7.7	100
Denmark	19	8.5	5.9	3.6	13	2.0	23	0.1	2.2	100
Ecuador	32	7.2	3.7	1.9	27	21	3.6	2.7	0.2	100
Finland	39	13	12	2.2	1.7	0.9	17	0.1	2.8	100
Germany	26	8.3	7.6	–	50	–	4.7	0.1	1.4	100
Hungary	26	6.5	6.8	0.6	27	4.4	17	2.5	2.2	100
Ireland	45	5.3	11	2.5	0.8	1.7	24	0.4	0.2	100
Italy	33	14	4.0	0.6	23	2.3	12	3.2	3.2	100
Japan	24	7.0	3.9	–	8.1	–	6.0	5.3	11	100
Kuwait	7.1	20	2.1	–	31	16	7.7	0.6	0.4	100
Lithuania	3.2	0.1	0.2	0	16	16	10	1.3	0.01	100
Netherlands	39	20	7.0	7.3	5.3	3.1	7.6	0.6	1.6	100
New Zealand	49	7.3	9.0	6.9	7.9	0.3	10	1.0	3.0	100
Panama	5.2	5.7	5.5	6.5	50	11	7.1	5.0	3.8	100
Qatar	25	20	3.5	–	12	–	29	1.4	0	100
Romania	12	–	1.0	–	27	20	9.4	26	3.5	100
Slovakia	29	2.6	16	–	27	0.05	9.4	6.6	0.5	100
Slovenia	18	12	7.3	4.0	23	3.4	13	1.5	4.3	100
Sweden	28	7.9	11	4.4	9.0	3.8	3.1	0.6	0.7	100
Switzerland	43	5.6	14	6.4	15	–	4.2	0.5	1.8	100
United Arab Emirates	27	15	2.3	0.3	13	13	19	1.3	0.6	100
United States	24	13	16	–	–	–	3.2	22	11	100
Average [a]	26	15	10	2.0	23	5.3	5.0	12	7.3	100
Health-care level II										
Jordan	22	0.7	0.5	0.3	47	11	11	2.6	–	100
Mexico	15	30	2.2	1.4	13	2.1	15	8.8	7.1	100
Oman	26	0	3.1	0.1	6.8	7.9	34	0.6	0	100
Pakistan	13	1.3	0.6	0	41	3.6	12	10	5.9	100

Table 39 (continued)

Country / area	*Bone*	*Cardiovascular*	*Lung perfusion*	*Lung ventilation*	*Thyroid scan*	*Thyroid uptake*	*Renal*	*Liver/spleen*	*Brain*	*Total of all procedures*
Health-care level II (continued)										
Peru	70	1.2	1.5	0.6	17	3.5	2.6	2.9	0.6	100
Tunisia	4.2	2.5	7.1	0	71	7.1	7.1	0	0	100
Turkey	24	14	1.8	1.1	26	–	15	6.7	1.8	100
Average [a]	20	15	1.7	0.9	26	3.3	14	7.7	4.2	100
Health-care level III										
Ghana	4.1	–	–	–	44	–	1.3	1.7	49	100
Morocco	21	7.3	3.0	0	61	0	6.1	1.1	0	100
Sudan	13	0	0	0	54	0	16	5.4	11	100
Average [a]	19	6.4	2.7	0	59	0	7.0	1.6	3.7	100
Health-care level IV										
Ethiopia	0.7	0	0.5	0	34	34	1.9	1.8	27	100
United Republic of Tanzania	18	0	0.3	0	0	52	26	0	3.6	100
Average [a]	8.4	0	0.4	0	19	42	13	1.0	16	100

a Overall averages for sample calculated as total number of each particular type of examination divided by total number of all examinations.

Table 40
Distribution by age and sex of patients undergoing diagnostic nuclear medicine procedures (1991-1996)
Data from UNSCEAR Survey of Medical Radiation Usage and Exposures unless otherwise indicated

Health-care level	*Country*	*Age distribution (%)*			*Sex distribution (%)*	
		0–15 years	*16–40 years*	*>40 years*	*Male*	*Female*
Bone scan						
I	Argentina	6	22	72	41	59
	Bulgaria	0	22	78	41	59
	Canada	6	15	79	50	50
	Croatia	4	33	63	47	53
	Czech Republic	7	7	86	41	59
	Ecuador	9	34	57	44	56
	Finland	3	–	–	–	–
	Ireland	<1	–	–	–	–
	Italy	1	8	91	34	66
	Japan	–	–	–	56	44
	Kuwait	8	42	50	58	42
	New Zealand [L28]	6	23	71	–	–
	Panama	12	18	70	52	48
	Romania	17	12	71	36	64
	Slovakia	3	37	60	–	–
	Slovenia	3	13	84	45	55
	Sweden	3	–	–	–	–
	United Arab Emirates	12	44	44	53	47
	Average	5	15	80	48	52
II	Jordan	3	32	65	20	80
	Mexico	7	18	75	45	55
	Pakistan	19	38	43	49	51
	Peru	10	30	60	30	70
	Turkey	6	28	66	52	48
	Average	9	27	64	46	54
III	Morocco	0	100	0	30	70
	Sudan	0	80	20	25	75
	Average	0	98	2	30	70
IV	Ethiopia	17	66	17	67	33
	United Rep. of Tanzania	4	24	72	36	64
	Average	5	26	69	37	63
Cardiovascular scan						
I	Argentina	0	12	88	68	32
	Bulgaria	0	22	78	62	38
	Canada	0	6	94	58	42
	Croatia	5	38	57	64	36
	Czech Republic	13	22	65	54	46
	Ecuador	0	19	81	66	34
	Finland	3	–	–	–	–
	Italy	0	11	89	76	24
	Japan	–	–	–	63	37
	Kuwait	0	20	80	73	27
	New Zealand [L28]	1	7	92	0	0
	Panama	14	30	56	30	70
	Slovakia	0	30	70	–	–
	Slovenia	0	8	92	–	–
	United Arab Emirates	0	42	58	38	62
	Average	0	7	93	60	40
II	Jordan	0	14	86	50	50
	Mecixo	0	14	86	58	42
	Pakistan	0	14	86	80	30
	Peru	0	40	60	45	55
	Turkey	0	11	89	60	40

Table 40 (continued)

Health-care level	*Country*	*Age distribution (%)*			*Sex distribution (%)*	
		0–15 years	*16–40 years*	*>40 years*	*Male*	*Female*
	Average	0	13	87	59	41
III	Morocco	0	100	0	–	–
Lung perfusion study						
I	Argentina	6	10	84	47	53
	Bulgaria	25	50	25	50	50
	Canada	2	17	81	51	49
	Croatia	2	38	60	51	49
	Czech Republic	2	9	89	45	55
	Ecuador	1	38	61	46	54
	Finland	0.1	–	–	–	–
	Ireland	<1	–	–	–	–
	Italy	0	6	94	54	46
	Japan	–	–	–	49	51
	Kuwait	7	41	52	66	34
	New Zealand [L28]	1	17	82	–	–
	Panama	15	28	57	38	62
	Romania	1	28	71	77	23
	Slovakia	0	36	64	–	–
	Slovenia	1	10	89	–	–
	Sweden	0.3	–	–	–	–
	United Arab Emirates	15	45	40	60	40
	Average	2	13	85	49	51
II	Jordan	9	36	55	29	71
	Mexico	5	19	76	51	49
	Pakistan	18	31	51	57	43
	Peru	0	40	60	30	70
	Turkey	3	40	57	45	55
	Average	5	31	64	48	52
III	Morocco	90	–	–	–	–
IV	Ethiopia	0	75	25	50	50
	United Rep. of Tanzania	0	50	50	0	100
	Average	0	67	33	33	67
Lung ventilation study						
I	Argentina	4	10	86	47	53
	Bulgaria	17	66	17	58	42
	Canada	1	18	81	51	49
	Croatia	0	33	67	48	52
	Czech Republic	1	7	92	45	55
	Ecuador	0	40	60	40	60
	Finland	1	–	–	–	–
	Italy	0	6	94	54	46
	Panama	14	29	57	30	70
	Slovenia	1	14	85	–	–
	Sweden	0.1	–	–	–	–
	United Arab Emirates	23	23	54	64	36
	Average	2	15	83	50	50
II	Jordan	0	65	35	90	10
	Mexico	2	10	88	36	64
	Peru	0	40	60	30	70
	Turkey	0	33	67	67	33
	Average	1	23	76	52	48
Thyroid scan						
I	Argentina	3	53	44	18	82
	Bulgaria	4	48	48	10	90
	Canada	2	37	61	20	80
	Croatia	3	51	46	21	79
	Czech Republic	1	22	77	17	83

Table 40 (continued)

Health-care level	*Country*	*Age distribution (%)*			*Sex distribution (%)*	
		0–15 years	*16–40 years*	*>40 years*	*Male*	*Female*
I	Ecuador	5	46	49	17	83
	Finland	1	–	–	–	–
	Ireland	<1	–	–	–	–
	Italy	1	37	62	16	84
	Japan	–	–	–	19	81
	New Zealand [L28]	2	29	69	–	–
	Panama	18	39	43	17	83
	Romania	1	48	51	19	81
	Slovakia	2	45	53	–	–
	Slovenia	1	16	83	–	–
	United Arab Emirates	3	50	47	30	70
	Average	2	40	58	18	82
II	Jordan	13	63	24	7	93
	Mexico	7	51	42	23	77
	Pakistan	15	64	21	31	69
	Peru	15	32	53	37	63
	Turkey	1	64	35	13	87
	Average	8	61	31	22	78
III	Morocco	10	85	5	35	65
	Sudan	10	60	30	10	90
	Average	10	82	8	32	68
IV	Ethiopia	6	72	22	18	82
Thyroid uptake						
I	Argentina	4	50	46	13	87
	Bulgaria	4	50	46	19	81
	Canada	3	39	58	21	79
	Croatia	0	37	63	19	81
	Czech Republic	0	15	85	15	85
	Ecuador	5	46	49	16	84
	Finland	0	–	–	–	–
	Ireland	<1	–	–	–	–
	Italy	1	37	62	16	84
	Japan	0	–	–	–	–
	Panama	4	45	51	22	78
	Romania	1	44	55	23	77
	Slovakia	0	23	77	–	–
	United Arab Emirates	3	50	47	30	70
	Average	3	41	56	18	82
II	Jordan	2	52	46	19	81
	Mexico	4	5	91	19	81
	Pakistan	9	53	38	41	59
	Peru	0	40	60	10	90
	Average	6	36	58	28	72
IV	Ethiopia	6	72	22	18	82
	United Rep. of Tanzania	3	31	66	16	84
	Average	4	50	46	17	83
Renal scan						
I	Argentina	7	41	52	47	53
	Bulgaria	3	56	41	48	52
	Canada	29	15	56	52	48
	Croatia	30	34	36	50	50
	Czech Republic	33	24	43	47	53
	Ecuador	22	47	31	55	45
	Finland	25	–	–	–	–
	Ireland	22	–	–	–	–
	Italy	14	21	65	54	46

Table 40 (continued)

Health-care level	*Country*	*Age distribution (%)*			*Sex distribution (%)*	
		0–15 years	*16–40 years*	*>40 years*	*Male*	*Female*
I	Kuwait	48	28	24	57	43
	New Zealand [L28]	33	24	43	–	–
	Panama	17	27	56	45	55
	Romania	1	35	64	40	60
	Slovakia	20	38	42	–	–
	Sweden	16	–	–	–	–
	United Arab Emirates	10	43	47	67	33
	Average	22	25	53	51	49
II	Jordan	50	21	29	53	47
	Mexico	12	41	47	39	61
	Pakistan	21	37	42	62	38
	Peru	61	23	16	50	50
	Turkey	36	46	18	74	26
	Average	26	42	32	60	40
III	Morocco	90	–	–	–	–
	Sudan	20	70	10	50	50
IV	Ethiopia	6	69	25	63	37
	United Rep. of Tanzania	7	45	48	38	62
	Average	7	47	46	40	60
Liver/spleen study						
I	Argentina	6	22	72	31	69
	Bulgaria	9	62	29	36	64
	Canada	16	16	68	55	45
	Croatia	0	37	63	50	50
	Czech Republic	14	25	61	48	52
	Ecuador	7	42	51	47	53
	Finland	1	–	–	–	–
	Italy	1	37	62	48	52
	Japan	–	–	–	62	38
	Kuwait	29	12	59	65	35
	Panama	4	11	85	54	46
	Romania	1	22	77	57	43
	Slovakia	5	30	65	–	–
	United Arab Emirates	5	20	75	45	55
	Average	7	26	67	56	44
II	Jordan	8	35	57	53	47
	Mexico	10	33	57	43	57
	Pakistan	12	41	47	50	50
	Peru	20	30	50	30	70
	Turkey	1	83	16	14	86
	Average	8	52	40	35	65
III	Morocco	100	0	0	–	–
	Sudan	0	5	95	25	75
	Average	60	2	38	25	75
IV	Ethiopia	0	67	33	73	27
Brain scan						
I	Argentina	4	10	86	33	67
	Bulgaria	54	34	12	48	52
	Canada	36	36	28	68	32
	Croatia	0	49	51	41	59
	Czech Republic	7	21	72	45	55
	Ecuador	0	100	0	50	50
	Finland	9	–	–	–	–
	Italy	0	10	90	53	47
	Japan	–	–	–	56	44
	Panama	33	24	43	40	60
	Romania	3	20	77	69	31

Table 40 (continued)

Health-care level	*Country*	*Age distribution (%)*			*Sex distribution (%)*	
		0–15 years	*16–40 years*	*>40 years*	*Male*	*Female*
I	Slovakia	8	46	46	–	–
	Sweden	20	–	–	–	–
	United Arab Emirates	0	42	58	42	58
	Average	18	25	57	56	43
II	Mexico	11	38	51	51	49
	Pakistan	25	40	35	55	45
	Peru	0	0	100	30	70
	Turkey	8	45	47	63	37
	Average	15	40	45	54	46
III	Sudan	0	10	90	30	70
IV	Ethiopia	9	67	24	60	40
	United Rep. of Tanzania	4	50	46	33	67
	Average	9	65	26	57	43
Other procedures						
I	Bulgaria (Testicles)	27	50	23	100	0
	Croatia (Infection)	0	41	59	42	58
	Croatia (GI bleeding)	2	42	56	58	42
	Croatia (Haemangioma)	0	37	63	35	65
	Coatia (Adrenal)	0	41	59	42	58
	Croatia (Biliary tract)	21	28	51	58	42
II	Peru (Cysternography)	50	30	20	30	70
	Peru (Gall bladder)	50	30	20	30	70
	Peru (VPT)	0	20	80	30	70
III	Morocco (sur. renal)	60	40	0	–	–
IV	Ethiopia (Meckel's divert.)	0	100	0	50	50
All diagnostic procedures						
I	Argentina	4	28	68	42	58
	Bulgaria	5	49	46	21	79
	Czech Republic	13	15	72	44	56
	Ecuador	7	39	54	33	67
	Finland	7	–	–	–	–
	Japan	3	9	88	49	51
	Netherlands	3	14	83	44	56
	New Zealand [L28]	7	21	72	–	–
	Panama	15	28	57	37	63
	Slovakia	3	39	58	–	–
	Ukraine	3	–	–	–	–
	United Arab Emirates	7	44	49	46	54
	Average	5	12	83	47	53
II	Mexico	8	28	64	45	55
IV	Ethiopia	7	70	23	31	69

The entries in this Table are qualified as follows:

Argentina: On the basis of data from a sample of 25% of nuclear medicine centres.
Canada: Data from London Health Sciences Centre, SW Ontario (representing 50% of the services provided to population of about 1 million).
Czech Republic: Survey data relating to Prague (about 10% of national population).
Jordan: Survey data from one hospital.
New Zealand: Data shown for 'Lung Perfusion' refer to both perfusion and ventiliation studies.
Peru: Survey data from IPEN (Centre of Nuclear Medicine, serving population of about 5 million).
Romania: Survey data relating to population base of about 4.5 million.
Slovakia: Survey data relating to population base of about 2 million.
Turkey: Survey data from Gülhane Military Hospital, Hacettepe University Hospital and Samsun Ondokuz Mayis University Hospital.

Table 41
Average activities administered in diagnostic examinations with radiopharmaceuticals (1991–1996)
Data from UNSCEAR Survey of Medical Radiation Usage and Exposures unless otherwise indicated

PART A

Country / area	*Average activity administered (MBq) (range or standard deviation in parentheses)*								
	Bone		*Cardiovascular*			*Brain*			
	^{99m}Tc phosphates	*^{99m}Tc other*	*^{99m}Tc MIBI*	*^{99m}Tc other*	*^{210}Tl chloride*	*^{99m}Tc DTPA*	*^{99m}Tc HMPAO*	*^{99m}Tc pertechnetate*	*Other*
Health-care level I									
Argentina	– [a]	781 [a] (± 192)	–	877 (±192)	89 (±11)	–	–	–	866 [d] (±137)
Belarus	–	720 [a] (680-760)	–	–	–	–	–	–	740 [d] (700–780)
Bulgaria	300 (150–450)	–	666	555 [b]	74	(550–740)	–	–	–
Canada	925 (±10%)	–	600 (±10%)	–	–	–	740 (±5%)	–	–
China, Taiwan Pr. [L6]	545 (370–750)	–	–	540 [c]	70	420	–	420	–
Croatia	555 (100–740)	–	–	370 [a] (185–740)	80 (70–111)	–	–	–	555 [d] (185–740)
Cyprus	630	–	–	600–1 100	75	–	–	–	–
Czech Republic	730 (350-1 210)	–	680	–	90 (80–100)	–	740 (460–860)	650 (600–700)	–
Denmark	637 (180–820)	–	615 (450–860)	710 [c] (73–1 110)	–	–	667 (125–945)	–	1629 [e] (60-3 000)
Ecuador	740 (±5%)	–	1 100 (±5%)	–	–	1 100 (±5%)	–	–	–
Finland	620	620 [a]	–	890 [a]	100	–	–	–	655 [d]; 124 [f]
France [E10]	–	–	1000	–	–	–	750	–	–
Germany	600	–	–	700 [c]	75	–	700	–	–
Ireland	500 (40–660)	–	–	800 [c] (600-1 100)	–	–	575 (550–600)	–	–
Italy	630 (555–740)	620 [b] (555–740)	600 (185–740)	–	90 (74–111)	630 (555–740)	720 (555–925)	–	–
Japan [J11]	–	740 [a]	–	740 [a]	131	740	787	–	650 [a] (740–555)
Kuwait	925 (740-1 110)	–	–	925 [c] (555–925)	–	–	555 (185–555)	–	–
Lithuania	600 (400–600)	–	–	–	–	–	–	–	–
Netherlands	–	500 [a] (400–800)	650 (600–700)	–	125 (100–150)	–	500	–	200 [f]
New Zealand [L28]	674 (50–920)	–	688 (341-1 080)	585 [c] (250–944)	80 (37–111)	744 (710–750)	705 (450–907)	740	–
Panama	555 (292–618)	–	555 (292–818)	–	–	555 (424–686)	–	–	–
Portugal [E10]	–	–	–	740 [a]	–	–	600	–	–
Romania	660 (480–840)	–	–	–	–	460 (330–590)	–	355 (210–500)	–
Slovakia	740 (260–740)	–	–	740 [a]	100	–	–	740 (200–740)	–
Slovenia	500 (370–740)	–	400 (37–555)	–	74	–	–	–	500 [d] (500–740)
Spain [E10]	740	–	740	–	–	–	740	–	–
Sweden	450 (60–600)	–	800 (400-1 400)	–	80 (60–120)	–	940 (600–1 000)	–	550 [g] (400–570)
Switzerland	670 (150-1 000)	–	570 (110–740)	–	80 (70–110)	–	610 (370–740)	620 (460–930)	930 [e]
United Arab Emirates	720 (74–820)	–	740 (700-1 000)	–	93 (80–95)	–	740 (700–760)	–	–
United Kingdom [A20]	600	–	300 (400 SPECT)	800 [c]	80	500 (800 SPECT)	–	500	500 [h]
Average	719	–	622	–	100	482	721	419	–

Table 41 (continued)

Country / area	*Average activity administered (MBq) (range or standard deviation in parentheses)*								
	Bone		*Cardiovascular*			*Brain*			
	^{99m}Tc phosphates	*^{99m}Tc other*	*^{99m}Tc MIBI*	*^{99m}Tc other*	*^{210}Tl chloride*	*^{99m}Tc DTPA*	*^{99m}Tc HMPAO*	*^{99m}Tc pertechnetate*	*Other*
Health-care level II									
Jordan	750 (±10%)	–	–	1000 [a]	75	–	–	–	–
Mexico	463 (185–740)	–	148 (111–185)	379 [b] (111–647)	–	262 (80–444)	262 (80–444)	–	–
Peru	740 (700–800)	–	740 (700–800)	740 [c] (700–800)	–	740 (700–800)	–	–	–
Turkey	851 (638-1 064)	–	1 221 (858-1 584)	–	97 (79–115)	–	601 (368–834)	–	–
Average	730	–	740	–	75	740	601	–	–
Health-care level III									
Ghana [A16]	446	–	–	–	–	–	–	409	–
Morocco	–	740 [a] (555–925)	–	925 [a]	92.5 (92.5–111)	–	–	–	–
Sudan	560	–	–	–	–	–	–	–	5 610 [d]
Average	546	–	–	–	93	–	–	–	–
Health-care level IV									
Ethiopia	555	–	–	–	–	666 (370–740)	–	666 (370–740)	–
United Rep. of Tanzania	600 (±5%)	–	–	–	–	800 (±5%)	–	–	–
Average	598	–	–	–	–	679	–	666	–

PART B

Country / area	*Average activity administered (MBq) (range in parentheses)*							
	Lung perfusion		*Lung ventilation*			*Liver/spleen*		
	^{99m}Tc MAA	*Other*	*^{99m}Tc DTPA*	*^{99m}Tc aerosol*	*Other*	*^{99m}Tc colloid*	*^{99m}Tc IDA*	*Other*
Health-care level I								
Argentina	–	181 [d] (±78); 200 [i]	–	–	988 [d] (±281)	–	–	229 [d] (±107)
Belarus	–	(±33)	–	–	–	–	–	120 [d] (111–129)
Bulgaria	74	–	925	–	–	185	333	–
Canada	185 (±10%)	–	–	–	–	111 (±10%)	–	–
China, Taiwan Pr. [L6]	120	–	–	–	–	150	140	–
Croatia	148 (111–222)	–	–	37 (17–74)	–	148 (74–222)	–	–

Table 41 (continued)

Country / area	*Average activity administered (MBq) (range in parentheses)*							
	Lung perfusion		*Lung ventilation*			*Liver/spleen*		
	^{99m}Tc MAA	*Other*	*^{99m}Tc DTPA*	*^{99m}Tc aerosol*	*Other*	*^{99m}Tc colloid*	*^{99m}Tc IDA*	*Other*
Cyprus	150	–	–	–	–	185	–	–
Czech Republic	188 (90–210)	–	970 (600–1 200)	–	–	148 (80–230)	–	–
Denmark	112 (50–185)	–	–	13 (7–80)	396 [e] (200–826)	83 (45–217)	–	–
Ecuador	870 (±5%)	–	370 (±5%)	–	–	370 (±10%)	–	–
Finland	105 [d]	460 [e]	–	–	580 [d]; 185 [e]	–	–	180 [d]
France [E10]	300	–	–	–	–	–	–	–
Germany	100	–	–	100	–	–	150	–
Ireland	80 (60–110)	–	80	–	–	110 (100–130)	110 (100–130)	–
Italy	150 (111–185)	–	555 (370–700)	–	–	150 (111–370)	–	148 [d] (111–185)
Japan [J11]	–	240 [d]	740	–	–	–	–	200 [d]
Kuwait	111 (74–185)	–	1 480 (1 110-1 850)	–	–	185 (74–185)	–	–
Lithuania	100 (80–100)	–	–	–	–	80 (80–100)	–	–
Netherlands	100	–	–	–	(450–750 min^{-1}) [j]	80	–	–
New Zealand [L28]	145 (56–286)	–	81 (37–136)		734 [e] (370–1 112)	196 (110–278)	–	–
Panama	185	–	925 (662–1188)	–	–	241 (110–372)	–	–
Portugal [E10]	111	–	–	444	–	185	–	–
Romania	125 (55–195)	–	–	–	–	140 (35–245)	–	9 [l] (7.4–10.6)
Slovakia	185 (80–185)	–	–	–	–	–	185	185 [d] (40–185)
Slovenia	170 (120–222)	74 [a] (37–84)	175 (84–185)	–	140 [e] (100–200)	–	180	(296–500) [d]
Spain [E10]	–	–	–	370	–	185	–	–
Sweden	100 (27–150)	–	200 (7–1 500)	240 (15-1 700)	–	170 (20–800)	–	–
Switzerland	140 (70–230)	–	–	–	390 [e] (110-750); 220 [k] (100-370)	120 (20–160)	100 (10–200)	
United Arab Emirates	140 (111–260)	–	222 (200–300)	–	–	148 (140–185)	–	–
United Kingdom [A20]	100 (200 SPECT)	–	80	–	400[e]; 6 000[j] (max)	80	–	–
Average	118	–	662	–	–	141	–	–
Health-care level II								
Jordan	150	–	1 000	–	–	150	–	–
Mexico	130 (74–185)	–	463 (185–740)	–	–	111 (36–185)	131 (40–222)	–
Peru	185 (150–200)	–	–	–	185 [a] (150–200)	185 (150–200)	–	–
Turkey	159 (124–194)	–	925	–	–	148 (96–200)	–	–
Average	147	–	703	–	–	150	–	–
Health-care level III								
Ghana [A16]	–	–	–	–	–	87	–	–
Morocco	–	185 [d] (185–259)	–	–	–	–	–	296 [d] (37–740)
Sudan	–	–	–	–	–	740	–	–
Average	–	–	–	–	–	454	–	–

Table 41 (continued)

Country / area	Average activity administered (MBq) (range in parentheses)							
	Lung perfusion		Lung ventilation			Liver/spleen		
	^{99m}Tc MAA	Other	^{99m}Tc DTPA	^{99m}Tc aerosol	Other	^{99m}Tc colloid	^{99m}Tc IDA	Other
Health-care level IV								
Ethiopia	111	–	–	–	–	111 (111–185)	–	–
United Rep. of Tanzania	–	1 180 [d] (±5%)	–	–	–	–	–	–
Average	111	–	–	–	–	111	–	–

PART C

Country / area	Average activity administered (MBq) (range in parentheses)									
	Thyroid scan			Thyroid uptake			Renal scan			
	^{99m}Tc pertechnetate	^{131}I iodide	Other	^{99m}Tc pertechnetate	^{131}I iodide	^{123}I iodide	^{99m}Tc DMSA	^{99m}Tc DTPA	^{99m}Tc MAG3	Other
Health-care level I										
Argentina	248 (±107)	3 (±1)	–	7 (±3)	2 (±1)	–	–	–	–	215[d] (±122); 6[n] (±2)
Belarus	111 (101-121)	–	–	–	0.4 (0.35-0.45)	–				185 [d] (174–196)
Bulgaria	(37–74)	–	(1–10) [m]	–	–	–	60 (40–80)	185 (85–285)	185 (85–285)	–
Canada	–	–	185 [d] (±10%)	–	–	–	–	400 (±15%)	–	–
China (Taiwan) [L6]	80	–	–	–	0.8	20	150	150	–	–
Croatia	148 (111-222)	148 (74–185)	–	–	17	–	74 (37–111)	74 (37–111)	–	–
Cyprus	–	75	150 [d]	–	75	–	75	220	–	–
Czech Republic	130 (70–180)	8 (8–12)	–	–	0.62 (0.4–1)	–	188 (80–250)	250 (110–360)	–	–
Denmark	150 (37–370)	–	–	–	86 (0.3-3 700)	–	–	165 (20–350)	92 (3–210)	–
Ecuador	–	3.7 (±10%)	–	–	3.7 (±10%)	–	–	370 (±10%)	370 (±10%)	–
Finland	130	–	12 [f]	–	3	6	–	–	–	9 [n]; 150 [d]
France [E10]	–	185	–	–	–	–	200	200 (74–740)	280	(74–740) [f]
Germany	50	–	–	50	–	–	75	–	–	25 [f]
Ireland	110 (27–130)	–	–	27 (11–72)	0.185	–	84 (26–185)	84 (26–185)	84 (26–185)	–
Italy	111 (74–185)	1.1 (0.74-1.85)	–	–	1.1 (0.74-1.85)	–	148 (111–180)	148 (111–180)	–	26 [n] (18.5–37)
Japan [J11]	–	26	200 [d]	192	23	8.8	197	377	–	49 [m]
Kuwait	185 (74–185)	–	–	–	1.5 (1.1–2.6)	–	–	370 (185–370)	370 (185–370)	–
Lithuania	–	60 (60–80)	–	–	–	–	150 (100–150)	–	–	–
Netherlands	100 (80–180)	–	20 [f]	–	0.2	20	–	(40–350)	80	–
New Zealand [L28]	168 (23-740)	113 (21–200)	–	–	5.5 (2–20)	–	65 (12–155)	314 (22–617)	228 (130–444)	3.3 [o] (1–5)
Panama	463 (332-594)	–	–	–	1.85	–	56 (30–82)	463 (432–594)	185 (107–263)	–
Portugal [E10]	–	–	–	–	–	–	111	111	111	111 [f]
Romania	90 (34–146)	1.6 (0.6–2.6)	–	–	1.3 (0.6–2)	–	–	300 (100–500)	–	1.5 [n] (0.7–2.3)

Table 41 (continued)

Country / area	*Average activity administered (MBq) (range in parentheses)*									
	Thyroid scan			*Thyroid uptake*			*Renal scan*			
	^{99m}Tc pertechnetate	*^{131}I iodide*	*Other*	*^{99m}Tc pertechnetate*	*^{131}I iodide*	*^{123}I iodide*	*^{99m}Tc DMSA*	*^{99m}Tc DTPA*	*^{99m}Tc MAG3*	*Other*
Slovakia	70 (40–110)	1.8 (0.18–1.8)	–	74	(0.18–1.8)	–	185 (80–370)	185 (80–370)	–	18.5 [n]
Slovenia	74 (37–74)	5 (3.7–7.4)	–	75 (50–100)	2 (1.5–3.7)	–	80	185	100	–
Spain [E10]	–	1.1	–	–	–	–	–	–	–	–
Sweden	120 (10–220)	2 (0.1–80)	–	–	2 (0.2–6)	–	40 (10–200)	–	85 (67–175)	–
Switzerland	90 (30–200)	2 (1–7)	13 [f] (5–20)	–	–	–	60 (20–130)	360 (10–800)	110 (100–150)	20 [f] (5–40)
United Arab Emirates	185 (148-260)	–	–	185 (148–260)	–	–	148 (140–185)	148 (140–185)	–	–
United Kingdom [A20]	80	20	–	40	0.2	2	80	300	100	3 [o]
Average	65	17	–	–	3.1	–	140	236	127	–
Health-care level II										
Jordan	–	–	–	–	3.7	–	140	740	–	–
Mexico	130 (74–185)	5.6 (3.8–7.4)	–	–	5.6 (3.8–7.4)	–	–	170 (80–259)	170 (80–259)	–
Peru	185 (150-200)	185 (150–200)	–	–	1 (0.5–1.2)	–	370 (300 min)	740 (700–800)	–	–
Turkey	134 (99–169)	–	–	–	–	–	161 (118–204)	321 (167–475)	–	–
Average	136	185	–	–	4.4	–	370	181	170	–
Health-care level III										
Ghana [A16]	97	–	–	–	–	–	–	99	–	–
Morocco	130 (93–167)	–	–	–	–	–	–	–	–	111 [d] (74–222)
Sudan	560	–	–	–	–	–	740	1800	–	–
Average	173	–	–	–	–	–	–	–	–	–
Health-care level IV										
Ethiopia	–	1.7 (1.3–2)	–	–	1.7 (1.3–2)	–	74	–	–	–
United Rep. of Tanzania	–	–	–	200	–	–	–	200	–	–
Average	–	1.7	–	–	1.7	–	74	200	–	–

a No further information available.
b Pertechnetate.
c Red blood cells.
d ^{99m}Tc.
e ^{133}Xe.
f ^{123}I.
g ^{11}C metiomin.
h ^{99m}Tc ECD.
i ^{67}Ga.
j ^{81m}Kr.
k ^{127}Xe.
l ^{128}Au colloid.
m ^{131}I, ^{125}I, ^{123}I.
n ^{131}I.
o ^{51}Cr EDTA.

Table 41 (continued)

The entries in this Table are qualified as follows:

Argentina: On the basis of data from a sample of 25% of nuclear medicine centres. Bone scans also performed using ^{67}Ga (204 ± 41 MBq).
Canada: Data from London Health Sciences Centre, SW Ontario (representing 50% of the services provided to population of about 1 million).
Cyprus Survey data relating to 90% of population.
Ghana: Data for thyroid scan refer to all thyroid studies.
Jordan: Survey data from one hospital.
Lithuania: Data from Vilnius Oncology Centre.
Morocco: Bone scans also performed using ^{131}I (mean 111 MBq; range 92.5–111 MBq).
Peru: Survey data from IPEN (Centre of Nuclear Medicine, serving population of about 5 million).
Portugal: Data from one large department and some additional data.
Romania: Survey data relating to population base of about 4.5 million. Alternative technique employed for bone scans using ^{99m}Tc phosphates: mean 110 MBq, range 60–160 MBq.
Slovakia: Survey data relating to population base of about 2 million.
Switzerland: Lung ventilation studies also performed using ^{127}Xe (mean 220 MBq; range 100–370 MBq).
Turkey: Survey data from Gülhane Military Hospital, Hacettepe University Hospital and Samsun Ondokuz Mayis University Hospital.
United Arab Emirates: Thyroid uptake done simultaneously with thyroid scan using a single dose.
United Kingdom: Data represent recommended maximum usual activities (diagnostic reference levels).

Table 42
Typical effective doses to patients from common types of diagnostic nuclear medicine procedures

Country	*Effective dose per procedure (mSv)*								
	Bone [a]	*Cardiovascular*	*Lung perfusion* [b]	*Lung ventilation*	*Thyroid scan*	*Thyroid uptake*	*Renal* [c]	*Liver / spleen* [c]	*Brain* [c]
Health-care level I									
Canada [A15]	4.3	4.9 (^{99m}Tc) 11.8 (^{201}Tl)	1.5	1.0 (^{99m}Tc)	1.7 (^{123}I)	–	0.5 (DTPA) 1.6 (MAG3) 1.3 (DMSA)	1.7 (S colloid)	6.9 (HMPAO)
China, Taiwan Province [L6]	3.3	3.2 (^{99m}Tc) 13.3 (^{201}Tl)	1.4	–	1.1 (^{99m}Tc)	14.4 (^{131}I)	0.84	1.2 (colloid) 2.1 (HIDA)	2.4
Germany [K12]	3.5	4.6 (^{99m}Tc) 17 (^{201}Tl)	1.1	–	0.6 (^{99m}Tc)	–	0.3 (^{123}I) 0.7 (DMSA)	2.3 (HIDA)	6.6 (HMPAO)
Romania [I36]	3.4	–	1.4	–	1.1 (^{99m}Tc) 38.4 (^{131}I)	31.2 (^{131}I)	0.1 (^{131}I) 1.6 (DTPA)	9.9 (^{198}Au) 1.4 (colloid)	2.0
New Zealand [L28]	4.3	3.9 (^{99m}Tc RBC) 7.6 (^{99m}Tc MIBI)	1.6	0.4 (DTPA)	2.0 (^{99m}Tc)	–	2.0 (DTPA) 0.6 (DMSA)	1.8 (Sn colloid)	4.8 (DTPA)

Table 42 (continued)

Country	*Effective dose per procedure (mSv)*								
	Bone [a]	*Cardiovascular*	*Lung perfusion* [b]	*Lung ventilation*	*Thyroid scan*	*Thyroid uptake*	*Renal* [c]	*Liver / spleen* [c]	*Brain* [c]
Slovakia [F8]	6.5	7.4 (^{99m}Tc RBC) 20.3 (^{201}Tl)	1.8	–	8.9	4.4	0.5	2.1	8.8
Sweden [M87]	3.5	10 (^{99m}Tc MIBI) 20 (^{201}Tl)	1.1	0.2 (^{99m}Tc)	2.4 (^{99m}Tc)	72 [d] (3 MBq ^{131}I) 6 [d] (0.5 MBq ^{131}I)	0.7 (MAG3) 0.008 (^{51}Cr EDTA)	–	8.4 (HMPAO)
United Kingdom [A20]	3 (5 [e])	8 (^{99m}Tc) 18 (^{201}Tl)	1 (2 [e])	0.2 (^{81m}Kr) 0.4 (^{99m}Tc) 0.4 (^{133}Xe)	1 (^{99m}Tc)	6 (^{131}I) 0.4 (^{123}I) 0.5 (^{99m}Tc)	2 (DTPA) 0.7 (DMSA) 0.7 (MAG3) 0.2 (^{123}I)	0.8 (2 [e]) (colloid)	5
United States [I23]	4.4	10.4 (^{201}Tl)	–	–	2 (^{99m}Tc) 59 (^{131}I) 0.2 (^{123}I)	–	4.8 (DTPA) 0.5 (^{131}I)	–	–
Health-care level II									
Iran (Islam. Rep. of) [M10]	6.5	2.9 (^{99m}Tc) 6.9 (^{201}Tl)	2.5	–	1.4 (^{99m}Tc) 25 (^{131}I) [f]	14.6 (^{131}I)	3.3 (DTPA) 10 (DMSA)	1.9 (S colloid) 0.6 (^{113m}In)	12.4 (TcO_4) 5.9 (DTPA)
Health-care level III									
Ghana [A16]	2.85	–	–	–	1 (^{99m}Tc)	–	0.4	0.62	5.4

a ^{99m}Tc phosphonates.
b ^{99m}Tc MAA.
c ^{99m}Tc.
d 35% uptake.
e SPECT.
f Uptake and scan.

Table 43
Typical effective doses to patients from diagnostic PET imaging
[A20]

Radionuclide	*Chemical form*	*Investigation*	*Administered activity (MBq)*	*Effective dose (mSv)*	*Dose to uterus (mGy)*
^{11}C	L-methyl-methionine	Brain tumour imaging	400	2	1
^{11}C	L-methyl-methionine	Parathyroid imaging	400	2	1
^{13}N	Ammonia	Myocardial blood flow imaging	550	2	1
^{15}O	Water (bolus)	Cerebral blood flow imaging	2 000	2	1
^{15}O	Water (bolus)	Myocardial blood flow imaging	2 000	2	1
^{18}F	FDG	Tumour imaging	400	10	7
^{18}F	FDG	Myocardial imaging	400	10	7
^{18}F	Fluoride	Bone imaging	250	7	5

Table 44
Typical effective doses to paediatric patients from diagnostic nuclear medicine procedures
[G47]

Radiopharmaceutical	*Activity for adult patient (MBq)*	*Effective dose per procedure by patient age [a] (mSv)*				
		Adult 70 kg [1.0]	*15 years-old 55 kg [0.9]*	*10 years-old 33 kg [0.69]*	*5 years-old 18 kg [0.44]*	*1 year-old 10 kg [0.27]*
^{99m}Tc-MAG3 (normal renal function)	100	0.7	0.8	0.7	0.6	0.6
^{99m}Tc-MAG3 (abnormal renal function)	100	0.6	0.7	0.7	0.5	0.5
^{99m}Tc-DTPA (normal renal function)	300	1.6	1.8	2.1	1.8	2.2
^{99m}Tc-DTPA (abnormal renal function)	300	1.4	1.6	1.9	1.8	2.0
^{99m}Tc-DMSA (normal renal function)	80	0.7	0.7	0.8	0.8	0.8
^{99m}Tc-pertechnetate (no thryoid block)	80	1.0	1.2	1.3	1.4	1.4
^{99m}Tc-IDA (normal biliary function)	150	2.3	2.4	2.9	3.0	3.7
^{99m}Tc-HMPAO	500	4.7	5.0	5.9	5.7	6.5
^{99m}Tc-leukocytes	200	2.2	2.7	3.0	2.9	3.4
^{99m}Tc-erythrocytes	800	5.3	6.0	6.6	6.7	7.6
^{99m}Tc-phosphates	600	3.6	3.7	4.1	4.2	4.9
^{99m}Tc-MIBI (resting)	400	3.3	4.0	4.4	4.8	5.4
^{201}Tl-chloride	80	20	30	129	95	86
^{123}I-iodide (55% thyroid uptake)	20	7.2	10.2	12.1	16.3	18.8
^{123}I-iodide (total thyroid block)	20	0.2	0.3	0.3	0.3	0.3
^{123}I-MIBG (no impurity)	400	5.6	6.5	9.1	8.8	10.1
^{67}Ga-citrate	150	15	18.9	22.8	23.1	27.9

a Figures in brackets are scaling factors for activity based on body weights shown. Doses calculated using age-specific coefficients from [I19].

Table 45
Some reported annual individual and collective effective doses from diagnostic nuclear medicine procedures [a]
Data from UNSCEAR Survey of Medical Radiation Usage and Exposures unless otherwise indicated

Country /area	*Effective dose (mSv)*		*Collective effective dose (man Sv)*	*Ref.*
	Per examination	*Per caput*		
Health-care level I				
Australia	5.3	0.064	1 110	[C7]
Canada	4	0.16	4 500	[A15]
China, Taiwan Province	4.4	0.029	600	[L6]
Finland	4.0	0.04	207	[K59]
Germany	3	0.1	5 000 [b]	[K12]
Netherlands	4.2	0.067	1 000	-
New Zealand	3.1	0.026	90	[L28]
Romania	16.2	0.049	1 124	[I36]
Russian Federation	5.4	0.075	10 000	-
Slovakia	4.0	0.022	111	[F8]
Switzerland	4.2	0.04	300	[R18]
Ukraine	1.2	0.006	320	[K18]
United Kingdom	4.2	0.036	2 000	[E11]
United States	4.4	0.14	35 400	[I23]
Health-care level II				
Iran (Islam. Rep. of)	4.3	0.008	450	[M10]
Health-care level III				
Ghana	3	0.0002	3	[A16]

a Since, as discussed in Section I.C, many of these exposures are received by patients nearing the end of their lives and the doses are not distributed evenly amongst the population, these doses should not be used for the assessment of detriment.
b Collective dose data refer only to states of former Federal Republic of Germany.

Table 46
Frequencies, effective doses and collective doses [a] assumed in global model for diagnostic practice with radiopharmaceuticals [b] (1991-1996)

Procedure	*Number of procedures per 1,000 population*					*Effective dose per procedure (mSv)*					*Annual collective dose (man Sv)*				
	Level I	*Level II*	*Level III*	*Level IV*	*World*	*Level I*	*Level II*	*Level III*	*Level IV*	*World*	*Level I*	*Level II*	*Level III*	*Level III*	*World*
Bone	4.5	0.24	0.053	0.001	1.3	4.5	4.5	4	4	4.5	31 000	3 300	140	3	35 000
Cardiovascular	2.7	0.17	0.018	0.00002	0.80	8	8	12	12	8	33 000	4 150	140	0.1	37 000
Lung perfusion	1.8	0.023	0.007	0.0001	0.49	1.5	2	2	2	1.5	4 150	140	9	0.1	4 300
Lung ventilation	0.34	0.011	0.0003	0.00002	0.095	1	1	1	1	1	520	35	0.2	0.01	600
Thyroid scan	4.1	0.30	0.16	0.003	1.3	2	10	30	30	3.4	12 500	9 300	3 200	55	25 000
Thyroid uptake	0.92	0.038	-	0.007	0.26	15	20	30	30	15	21 000	2 400	-	120	24 000
Renal	0.89	0.16	0.020	0.002	0.32	1.5	3	3	3	1.9	2 000	1 500	40	4	3 500
Liver / spleen	2.1	0.090	0.005	0.0002	0.59	1.7	2	2	2	1.7	5 300	600	6	0.2	5 900
Brain	1.3	0.050	0.010	0.003	0.37	6	6	6	6	6	12 000	900	40	9	13 000
Total	19	1.1	0.28	0.02	5.6	-	-	-	-	-	123 000	23 000	3 500	200	150 000
Average effective dose per diagnostic nuclear medicine procedure (mSv)						4.3	6.7	20	20	4.6					
Average effective dose per caput from diagnostic nuclear medicine procedures (mSv)											0.081	0.008	0.006	0.0003	0.026

a Since, as discussed in Section I.C, many of these exposures are received by patients nearing the end of their lives and the doses are not distributed evenly amongst the population, these doses should not be used for the assessment of detriment.

b Rounded estimates based on frequency data and typical (or assumed) doses from the UNSCEAR Survey of Medical Radiation Usage and Exposures.

Table 47
Contributions to frequency and collective dose from the various types of diagnostic nuclear medicine procedures assumed for global model (1991-1996)

Procedure	*Contribution (%)*				
	Level I	*Level II*	*Level III*	*Level IV*	*World*
Contribution to total annual frequency					
Bone	24	21	19	8	24
Cardiovascular	14	15	6	0.1	14
Lung perfusion	10	2	2	0.4	9
Lung ventilation	2	1	0.1	0.1	2
Thyroid scan	22	27	59	19	22
Thyroid uptake	5	3	-	42	5
Renal	5	14	7	13	6
Liver / spleen	11	8	2	1	11
Brain	7	4	4	16	7
All	100	100	100	100	100
Contribution to total annual collective dose					
Bone	25	14	4	2	23
Cardiovascular	27	18	4	0.1	25
Lung perfusion	3	0.6	0.3	<0.1	3
Lung ventilation	0.4	0.1	<0.1	<0.1	0.4
Thyroid scan	10	40	89	28	17
Thyroid uptake	17	10	-	62	16
Renal	2	6	1	2	2
Liver / spleen	4	2	0.2	0.1	4
Brain	10	4	1	5	8
All	100	100	100	100	100

Table 48
Temporal trends in annual frequency of diagnostic nuclear medicine procedures per 1,000 population
Data from UNSCEAR Surveys of Medical Radiation Usage and Exposures

Country / area	*1970–1979*	*1980–1984*	*1985–1990*	*1991–1996*
Health-care level I				
Argentina	–	–	11.5	11.1
Australia	3.8	8.9	8.3	12.0
Austria	18.0	–	–	–
Belarus	–	–	–	0.5
Belgium	–	–	36.8	–
Bulgaria	–	13.0	–	3.3
Canada	–	–	12.6	64.6
Cayman Islands	–	–	–	0
China, Taiwan Province	–	–	–	6.6
Croatia	–	–	–	2.4
Cuba [a]	(0.8)	–	–	–
Cyprus	–	–	–	6.6
Czechoslovakia [b]	13.6	18.3	22.9	–
Czech Republic	–	–	–	28.3
Denmark	14.0	14.2	13.4	15.2
Ecuador [a]	(0.5)	–	(0.8)	0.8
Estonia	–	–	–	8.0
Finland	12.6	17.7	–	10.0
France	–	9.0	6.9	–
Germany [c]	31.1	39.7	39.8	34.1
Hungary	–	–	–	15.3
Ireland	–	–	–	6.1
Italy	6.0	–	7.3	11.0
Japan	–	–	8.3	11.7

Table 48, continued

Country / area	*1970–1979*	*1980–1984*	*1985–1990*	*1991–1996*
Kuwait	–	–	13.1	12.7
Lithuania	–	–	–	10.6
Luxembourg	–	–	23.5	52.2
Netherlands	–	–	11.6	15.7
New Zealand	5.6	7.3	7.5	8.3
Norway	3.9	–	9.3	–
Panama	–	–	–	3.4
Portugal	–	–	–	4.0
Qatar	–	–	–	4.7
Romania	–	3.0	3.5	3.0
Russian Federation [d]	(9)	(11)	(15)	12.6
Slovakia [d]	–	–	(4.9)	9.4
Slovenia	–	–	–	11.2
Sweden	9.8	–	12.6	13.6
Switzerland	44.9	–	–	9.5
Ukraine	–	–	–	5.0
United Arab Emirates	–	–	–	7.2
United Kingdom	–	6.8	–	8.2
United States	–	–	25.7	31.5
Yugoslavia	–	–	6.1	–
Average	11	6.9	16	19
Health-care level II				
Antigua and Barbuda	–	–	–	0
Barbados	–	–	1.0	–
Brazil	–	–	1.7	1.1
China	–	–	0.6	–
Dominica	–	–	–	0
Grenada	–	–	–	0
India	–	0.1	0.2	–
Iran (Islamic Rep. of)	–	–	–	1.9
Iraq	–	–	1.2	–
Jordan	–	–	–	1.6
Mexico	–	–	–	1.1
Oman	–	–	–	0.6
Pakistan	–	–	–	0.6
Peru	–	–	0.2	0.6
Saint Kitts and Nevis	–	–	–	0
Saint Lucia	–	–	–	0
Saint Vincent and the Grenadines	–	–	–	0
Tunisia	–	–	1.0	0.8
Turkey	–	–	2.5	2.1
Average	0.9	0.1	0.5	1.1
Health-care level III				
Egypt	0.07	0.21	0.48	–
Ghana	–	–	–	0.05
Jamaica [a]	(2.8)	–	(2.0)	–
Morocco	–	–	–	0.62
Myanmar	0.54	0.36	0.11	–
Sudan	0.12	0.28	0.28	0.09
Thailand	0.25	0.18	0.26	–
Average	0.25	0.25	0.30	0.28
Health-care level IV				
Ethiopia	–	0.014	0.10	0.014
United Rep. of Tanzania	–	–	–	0.024
Average	–	–	–	0.02

a Categorized in health-care level II in previous analyses.
b Historical data.
c Historical data for 1970–1979, 1980–1984 and 1985–1990 refer to Federal Republic of Germany.
d Historical data were not included in previous analyses.

Table 49
Temporal trends in the average annual number [a] of the various types of diagnostic radionuclide procedures per 1,000 population
Data from UNSCEAR Surveys of Medical Radiation Usage and Exposures

Type of study	*Period*	*Average annual number of procedures per 1,000 population*			
		Health-care level I	*Health-care level II*	*Health-care level III*	*Health-care level IV*
Bone scan	1970–1979	0.84	0	0.001	0.001
	1980–1984	2.6	–	0.041	0.041
	1985–1990	4.8	0.016	0.084	0.084
	1991–1996	5.8	0.20	0.054	0.001
Cardiovascular	1970–1979	0.53	0	0.0007	0.0007
	1980–1984	0.58	–	0.003	0.003
	1985–1990	2.6	0.008	0.014	0.014
	1991–1996	3.6	0.15	0.023	0
Lung perfusion	1970–1979	0.34	0.024	0.0003	0.0003
	1980–1984	0.94	–	0.002	0.002
	1985–1990	2.2	0.002	0.008	0.008
	1991–1996	2.3	0.017	0.009	0.0001
Lung ventilation	1970–1979	0.13	0	0.0001	0.0001
	1980–1984	0.26	–	0.0001	0.0001
	1985–1990	1.2	0.001	0.008	0.008
	1991–1996	0.35	0.009	0	0
Thyroid scan	1970–1979	1.3	0.4	0.066	0.066
	1980–1984	2.5	–	0.048	0.048
	1985–1990	1.8	0.062	0.066	0.066
	1991–1996	4.0	0.26	0.16	0.003
Thyroid uptake	1970–1979	2.2	0.25	0.10	0.10
	1980–1984	0.17	–	0.063	0.063
	1985–1990	0.55	0.17	0.052	0.052
	1991–1996	0.80	0.03	0	0.007
Renal	1970–1979	1.8	0.041	0.006	0.006
	1980–1984	1.3	–	0.009	0.009
	1985–1990	1.4	0.096	0.023	0.023
	1991–1996	1.1	0.14	0.019	0.002
Liver / spleen	1970–1979	1.7	0.087	0.086	0.086
	1980–1984	1.2	–	0.034	0.034
	1985–1990	1.4	0.023	0.016	0.016
	1991–1996	2.6	0.078	0.004	0.0002
Brain	1970–1979	1.3	0.23	0.022	0.022
	1980–1984	1.1	–	0.013	0.013
	1985–1990	0.42	0.006	0.007	0.007
	1991–1996	1.6	0.04	0.010	0.003
Total of all diagnostic radionuclide procedures	1970–1979	10.9	0.86	0.25	0.25
	1980–1984	6.9	0.10	0.19	0.19
	1985–1990	16.2	0.54	0.25	0.25
	1991–1996	18.8	1.13	0.28	0.02

a Overall averages calculated from national data as the total number of procedures divided by the total population for each type of procedure. Data for 1991–1996 from Table 38; since the total population is not the same for each type of procedure due to the lack of comprehensive national data for all countries included in the analysis, these average numbers can not be expected to be additive.

Table 50
Estimated doses to the world population from diagnostic nuclear medicine procedures [a] 1991–1996

Health-care level	*Population (millions)*	*Annual per caput effective dose (mSv)*	*Annual collective effective dose (man Sv)*
I	1 530	0.08	123 000
II	3 070	0.008	23 000
III	640	0.006	3 500
IV	565	0.0003	200
World	5 800	0.03	150 000

a Since, as discussed in Section I.C, many of these exposures are received by patients nearing the end of their lives and the doses are not distributed evenly amongst the population, these doses should not be used for the assessment of detriment.

Table 51
Annual numbers of teletherapy treatments [a] per 1,000 population by disease category (1991-1996)
Data from UNSCEAR Survey of Medical Radiation Usage and Exposures unless otherwise indicated

Country / area	*Leukaemia*	*Lymphoma*	*Breast tumour*	*Lung/ thorax tumour*	*Gynae-cological tumour*	*Head/neck tumour*	*Brain tumour*	*Skin tumour*	*Bladder tumour*	*Prostate tumour*	*Tumour of rectum*	*Benign disease*	*Total of all teletherapy treatments*
Health-care level I													
Australia	0.051	0.058	0.320	0.281	0.099	0.153	0.045	0.123	0.039	0.154	0.069	0.050	1.838
Belarus	0.001	0.027	0.078	0.082	0.073	0.056	0.011	0.033	0.017	0.006	0.019	-	0.454
Bulgaria	0.004	0.005	0.061	0.007	0.033	0.024	0.004	0.003	0.001	-	0.003	0.030	0.185
Canada	0.008	0.158	0.351	0.442	0.101	0.082	0.036	0.045	0.029	0.120	0.051	0.036	1.693
Cayman Islands	0	0	0	0	0	0	0	0	0	0	0	0	0
Croatia	0.001	0.063	0.789	0.182	0.194	0.273	0.059	0.131	0.017	0.012	0.060	0.004	1.981
Cuba [b] [B43]	-	-	-	-	-	-	-	-	-	-	-	-	2.036
Cyprus	0.003	0.018	0.256	0.077	0.028	0.015	0.031	0.184	0.015	0.034	0.031	0.006	0.929
Czech Republic	0.008	0.029	0.197	0.141	0.166	0.057	0.029	0.044	0.021	0.027	0.081	2.68	3.493
Denmark	0.029	0.098	0.275	0.069	0.157	0.275	0.098	0.059	0.078	0	0.049	-	1.539
Ecuador	0.004	0.007	0.015	0.003	0.040	0.010	0.007	0.003	0.002	0.003	0.005	0.0006	0.104
France [S50]	-	-	-	-	-	-	-	-	-	-	-	-	1.734
Hungary	-	-	-	-	-	-	-	0.431	-	-	-	1.214	3.655
Ireland	0.005	0.070	0.267	0.180	0.095	0.127	0.044	0.070	0.019	0.050	0.065	-	1.619
Japan [c]	-	0.050	0.083	0.178	0.059	0.065	0.028	-	0.015	0.019	0.099	-	0.762
Kuwait	0.018	0.015	0.063	0.022	0.016	0.033	0.010	0.0006	0.007	0.009	0.007	0	0.228
Luxembourg	0	0	0	0	0	0	0	0	0	0	0	0	0
Netherlands	-	0.053	0.553	0.447	0.122	0.103	0.024	0.083	0.225	-	0.073	0.021	2.2 [c]
New Zealand	0.017	0.092	0.395	0.231	0.077	0.064	0.040	0.220	0.035	0.259	0.103	0.025	1.715
Panama	0.006	0.005	0.058	0.031	0.077	0.059	0.022	0.003	0.003	0.023	0.008	0.001	0.295
Qatar	0	0	0	0	0	0	0	0	0	0	0	0	0
Romania	0.0009	0.006	0.106	0.053	0.114	0.061	0.012	0.060	0.004	0.003	0.012	0.002	0.461
Russian Federation	-	-	-	-	-	-	-	-	-	-	-	-	0.970
Slovakia	0.001	0.013	0.145	0.096	0.160	0.080	0.024	0.039	0.012	0.009	0.045	0.0008	0.764
Slovenia	0.011	0.081	0.232	0.341	0.188	0.242	0.030	0.120	0.026	0.034	0.061	0.017	2.437
Sweden	-	0.093	0.391	0.151	0.142	0.073	0.049	0.038	0.044	0.214	0.071	0.039	1.305
United Arab Emirates	0.007	0.011	0.046	0.021	0.016	0.027	0.011	0.004	0.010	0.008	0.006	0.003	0.231
United Kingdom	-	-	-	-	-	-	-	-	-	-	-	-	2.320
United States [I23]	0.001	0.069	0.494	0.548	0.135	0.033	0.056	0.013	0.046	0.282	0.074	0.017	1.981
Uruguay [d] [B43]	-	-	-	-	-	-	-	-	-	-	-	-	1.509
Venezuela [b] [B43]	-	-	-	-	-	-	-	-	-	-	-	-	1.603
Average	0.005	0.060	0.401	0.355	0.113	0.054	0.046	0.047	0.039	0.206	0.069	0.088	1.50

Table 51 (continued)

Country / area	*Leukaemia*	*Lymphoma*	*Breast tumour*	*Lung/ thorax tumour*	*Gynae-cological tumour*	*Head/neck tumour*	*Brain tumour*	*Skin tumour*	*Bladder tumour*	*Prostate tumour*	*Tumour of rectum*	*Benign disease*	*Total of all teletherapy treatments*
Health-care level II													
Antigua and Barbuda [B43]	-	-	-	-	-	-	-	-	-	-	-	-	0
Bahamas [B43]	-	-	-	-	-	-	-	-	-	-	-	-	0
Barbados [d] [B43]	-	-	-	-	-	-	-	-	-	-	-	-	3.132
Belize [B43]	-	-	-	-	-	-	-	-	-	-	-	-	0
Bolivia [d] [B43]	-	-	-	-	-	-	-	-	-	-	-	-	0.829
Brazil	-	-	-	-	-	-	-	-	-	-	-	-	1.333
Chile [b] [B43]	-	-	-	-	-	-	-	-	-	-	-	-	2.144
Colombia [b] [B43]	-	-	-	-	-	-	-	-	-	-	-	-	1.583
Dominica [B43]	-	-	-	-	-	-	-	-	-	-	-	-	0
Dominican Republic [b]	-	-	-	-	-	-	-	-	-	-	-	-	1.900
El Salvador [b] [B43]	-	-	-	-	-	-	-	-	-	-	-	-	2.025
Grenada [B43]	-	-	-	-	-	-	-	-	-	-	-	-	0
Honduras [b] [B43]	-	-	-	-	-	-	-	-	-	-	-	-	2.002
Jordan	0.018	0.026	0.052	0.024	0.013	0.023	0.022	0.004	0.009	0.006	0.009	0.005	0.268
Libyan Arab Jamahiriya	0.002	0.006	0.009	0.014	0.005	0.015	0.012	0.005	0.007	0.002	0.003	-	0.079
Mexico	0.005	0.005	0.025	0.007	0.029	0.016	0.006	0.003	0.001	0.004	0.002	0.002	0.111
Nicaragua [b] [B43]	-	-	-	-	-	-	-	-	-	-	-	-	2.196
Oman	0	0	0	0	0	0	0	0	0	0	0	0	0
Pakistan	0.003	0.004	0.007	0.004	0.005	0.010	0.002	0.003	0.002	0.002	0.002	0.0006	0.053
Paraguay [b] [B43]	-	-	-	-	-	-	-	-	-	-	-	-	2.126
Peru	0.002	0.007	0.013	0.006	0.068	0.013	0.006	0.002	0.001	0.004	0.002	-	0.139
Puerto Rico [b]	-	-	-	-	-	-	-	-	-	-	-	-	1.450
Saint Kitts and Nevis [B43]	-	-	-	-	-	-	-	-	-	-	-	-	0
Saint Lucia [B43]	-	-	-	-	-	-	-	-	-	-	-	-	0
Saint Vincent and the Grenadines [B43]	-	-	-	-	-	-	-	-	-	-	-	-	0
Trinidad and Tobago [d] [B43]	-	-	-	-	-	-	-	-	-	-	-	-	1.516
Tunisia	-	-	-	-	-	-	-	-	-	-	-	-	0.133
Turkey	0.022	0.024	0.066	0.056	0.029	0.044	0.039	0.006	0.010	0.006	0.011	0.002	0.385
Average	0.007	0.009	0.025	0.015	0.021	0.019	0.011	0.004	0.003	0.004	0.004	0.001	0.694
Health-care level III													
Afghanistan	-	-	-	-	-	-	-	-	-	-	-	-	0
Guatemala [b] [B43]	-	-	-	-	-	-	-	-	-	-	-	-	2.059
Haiti [b] [B43]	-	-	-	-	-	-	-	-	-	-	-	-	1.848
Jamaica [b] [B43]	-	-	-	-	-	-	-	-	-	-	-	-	2.059
Madagascar	0.0001	0.004	0.022	0.003	0.017	0.008	0.0001	0.002	0.0004	0.0008	0.002	0.002	0.065
Morocco	0.0009	-	-	-	-	-	-	-	-	-	-	-	0.360
Sudan	0.005	0.003	0.010	-	0.005	0.002	0.0006	0.001	0.002	-	0.0008	-	0.045
Average	0.002	0.003	0.014	0.003	0.009	0.004	0.0004	0.001	0.001	0.0008	0.001	0.002	0.465

Table 51 (continued)

Country / area	*Leukaemia*	*Lymphoma*	*Breast tumour*	*Lung/ thorax tumour*	*Gynae-cological tumour*	*Head/neck tumour*	*Brain tumour*	*Skin tumour*	*Bladder tumour*	*Prostate tumour*	*Tumour of rectum*	*Benign disease*	*Total of all teletherapy treatments*
Health-care level IV													
United Rep. of Tanzania	0.0004	0.003	0.003	0.004	0.020	0.001	0	0.003	0.0004	0.0005	0	0.002	0.050
Average	0.0004	0.003	0.003	0.004	0.020	0.001	0	0.003	0.0004	0.0005	0	0.002	0.050

a Complete courses of treatment.
b Data referring to number of new patients with cancer.
c These revised data were received by the Committee after completion of the global analysis.
d Data referring to estimated number of new patients with cancer.

The entries in this Table are qualified as follows:

Australia: Survey data from only 8 of 31 radiotherapy treatment centres (representing about 42% of national practice).
Brazil: Survey data for Paraná State (with a population of 9 million and a social and economic profile above the average for Brazil).
Canada: On the basis of data from the Nova Scotia Cancer Treatment and Research Foundation, the Cross Cancer Institute (Northern Alberta), and the province of Manitoba (collectively representing about 14% of the population).
Croatia: Data from one large centre serving about one-fifth of population.
France: Data represent annual number of patients undergoing radiotherapy [S50].
Peru: Survey data from INEN (Cancer Institute, Lima, serving population of about 7 million).
New Zealand: Data from 50% of radiotherapy centres (serving about two-thirds of population).
United Rep. of Tanzania: 98% of the total shown for 'Lung/thorax tumour' are treatments of the oesophagus.
Turkey: On the basis of data from Hacettepe University Hospital.
United States: Value shown for 'Benign' includes the general category of 'Others/Unspecified' [I23].

Table 52
Annual numbers of brachytherapy treatments [a] per 1,000 population by disease category (1991-1996)
Data from UNSCEAR Survey of Medical Radiation Usage and Exposures unless otherwise indicated

Country / area	*Head/neck tumour*	*Breast tumour*	*Gynaecological tumour*	*Prostate tumour*	*Total of all brachytherapy treatments*
Health-care level I					
Australia	0.001	0.002	0.055	0	0.064
Belarus	0.021	0.003	0.059	0.001	0.096
Bulgaria	-	-	-	-	0.556
Canada	0.001	0	0.055	0.009	0.070
Cayman Islands	0	0	0	0	0
Croatia	0	0	0.074	0	0.074
Cyprus	0	0	0.018	0	0.018
Czech Republic	0.002	0.010	0.247	0.0005	0.273
Denmark	-	-	0.009	-	-
Ecuador	0	0	0.010	0	0.010
Hungary	-	-	-	-	0.311
Ireland	0.004	0.0008	0.082	-	0.094
Kuwait	0	0	0.015	0	0.015
Luxembourg	0	0	0	0	0
Netherlands	0.008	0.062	0.027	0.003	0.15 [b]
New Zealand	0.005	0.002	0.035	0	0.047
Panama	0.001	0	0.051	0	0.053
Qatar	0	0	0	0	0
Romania	0.002	0.004	0.143	0.0007	0.162
Russian Federation	-	-	-	-	0.440
Slovakia	0.010	0.054	0.154	0.0004	0.258
Slovenia	0.044	0	0.088	0.001	0.140
Sweden	-	-	0.110	-	0.110
United Arab Emirates	0.002	0	0.007	0	0.009
United States [I23]	-	-	-	-	0.115
Uruguay	-	-	-	-	0
Average	0.005	0.011	0.078	0.002	0.20
Health-care level II					
Antigua and Barbuda [B43]	-	-	-	-	0
Bahamas [B43]	-	-	-	-	0
Belize [B43]	-	-	-	-	0
Dominica [B43]	-	-	-	-	0
Grenada [B43]	-	-	-	-	0
Mexico	0.002	0.004	0.0001	0	0.021
Oman	0	0	0	0	0
Pakistan	0	0	0.001	0	0.001
Paraguay	-	-	-	-	0
Peru	0	0	0.036	0	0.036
Saint Kitts and Nevis [B43]	-	-	-	-	0
Saint Lucia [B43]	-	-	-	-	0
Saint Vincent and the Grenadines [B43]	-	-	-	-	0
Tunisia	0.003	0	0.014	0	0.022
Turkey	0.003	0.002	0.028	-	0.037
Average	0.0008	0.0005	0.009	0	0.017
Health-care level III					
Jamaica [B43]	-	-	-	-	0
Morocco	-	-	0.030	-	0.030
Sudan	0	0	0.0009	0	0.0009
Average	0	0	0.016	0	0.015

a Complete courses of treatment.
b These revised data were received by the Committee after completion of the global analysis.

The entries in this Table are qualified as follows:

Australia: Survey data from only 8 of 31 radiotherapy treatment centres (representing about 42% of national practice).
Canada: On the basis of data from the Nova Scotia Cancer Treatment and Research Foundation, the Cross Cancer Institute (Northern Alberta), and the province of Manitoba (collectively representing about 14% of the population).
Croatia: Data from one large centre serving about one-fifth of population.
New Zealand: Data from 50% of radiotherapy centres (serving about two-thirds of population).
Peru: Survey data from INEN (Cancer Institute, Lima, serving population of about 7 million).
Turkey: On the basis of data from Hacettepe University Hospital.

Table 53
Percentage contributions by disease category to annual total numbers of teletherapy treatments [a] (1991-1996)
Based on data and qualifications from Table 51

Country	*Leukaemia*	*Lymphoma*	*Breast tumour*	*Lung/ thorax tumour*	*Gynae-cological tumour*	*Head/neck tumour*	*Brain tumour*	*Skin tumour*	*Bladder tumour*	*Prostate tumour*	*Tumour of rectum*	*Benign disease*	*Total of all teletherapy treatments*
Health-care level I													
Australia	2.8	3.2	17	15	5.4	8.3	2.5	6.7	2.2	8.4	3.7	2.8	100
Belarus	0.2	5.9	17	18	16	12	2.4	7.2	3.8	1.4	4.1	-	100
Bulgaria	2.2	2.7	33	3.6	18	13	1.9	1.9	0.6	-	1.6	16	100
Canada	0.5	9.3	21	26	6.0	4.8	2.2	2.7	1.7	7.1	3.0	2.1	100
Croatia	0.1	3.2	40	9.2	9.8	14	3.0	6.6	0.9	0.6	3.0	0.2	100
Cyprus	0.3	2.0	28	8.3	3.0	1.7	3.3	20	1.7	3.6	3.3	0.7	100
Czech Republic	0.2	0.8	5.6	4.0	4.8	1.6	0.8	1.3	0.6	0.8	2.3	77	100
Denmark	1.9	6.4	18	4.5	10	18	6.4	3.8	5.1	0	3.2	-	100
Ecuador	3.4	6.7	14	2.7	38	9.2	6.7	3.3	1.9	2.5	4.4	0.6	100
Hungary	-	-	-	-	-	-	-	12	-	-	-	33	100
Ireland	0.3	4.3	17	11	5.8	7.9	2.7	4.3	1.2	3.1	4.0	-	100
Japan	-	6.7	-	24	12	8.1	-	10	3.6	-	13	0.3	100
Kuwait	8.0	6.7	27	9.6	7.0	14	4.4	0.3	2.9	4.2	3.1	0	100
Netherlands	-	2.9	30	24	6.6	5.6	1.3	4.5	12	-	4.0	1.1	100
New Zealand	1.0	5.4	23	13	4.5	3.7	2.3	13	2.0	15	6.0	1.4	100
Panama	1.9	1.5	19	11	26	20	7.3	0.9	1.0	7.9	2.7	0.5	100
Romania	0.2	1.2	23	11	25	13	2.6	13	0.8	0.6	2.6	0.3	100

Table 53 (continued)

Country	*Leukaemia*	*Lymphoma*	*Breast tumour*	*Lung/ thorax tumour*	*Gynae-cological tumour*	*Head/neck tumour*	*Brain tumour*	*Skin tumour*	*Bladder tumour*	*Prostate tumour*	*Tumour of rectum*	*Benign disease*	*Total of all teletherapy treatments*
Slovakia	0.2	1.7	19	13	21	11	3.1	5.1	1.6	1.2	5.9	0.1	100
Slovenia	0.4	3.3	9.5	14	7.7	9.9	1.2	4.9	1.1	1.4	2.5	0.7	100
Sweden	-	7.1	30	12	11	5.6	3.8	2.9	3.3	16	5.4	3	100
United Arab Emirates	2.9	4.5	20	8.9	7.1	12	4.7	1.8	4.4	3.3	2.7	1.3	100
United States [I23]	0.1	3.5	25	28	6.8	1.7	2.8	0.7	2.3	14	3.7	0.9	100
Average [b]	0.3	4.1	23	24	7.7	3.7	2.7	3.1	2.7	12	4.7	5.8	100
Health-care level II													
Jordan	6.7	9.6	19	8.9	4.7	8.4	8.2	1.3	3.2	2.2	3.5	1.8	100
Libyan Arab Jamahiriya	2.7	8.0	12	18	6.1	19	15	6.1	8.3	2.4	3.7	-	100
Mexico	4.1	4.1	22	6.3	26	15	5.6	3.0	1.3	3.9	2.2	1.5	100
Pakistan	6.2	7.5	14	7.0	8.8	18	4.0	6.3	3.5	2.7	2.7	1.2	100
Peru	1.3	5.3	9.4	4.6	48	9.2	4.6	1.1	0.7	3.1	1.6	-	100
Turkey	5.7	6.3	17	14	7.5	11	10	1.5	2.5	1.7	3.0	0.6	100
Average [b]	5.1	6.0	17	11	14	13	7.8	2.6	2.3	2.4	2.7	0.9	100
Health-care level III													
Madagascar	0.2	6.6	34	4.7	26	13	0.2	2.5	0.6	1.2	2.8	3.3	100
Morocco	0.3	-	-	-	-	-	-	-	-	-	-	-	100
Sudan	11	5.5	22	-	11	4.2	1.3	2.4	3.7	-	1.8	-	100
Average [b]	1.4	6.0	28	4.7	18	7.8	0.8	2.5	2.3	1.2	2.2	3.3	100
Health-care level IV													
United Rep. of Tanzania	0.7	6.6	5.0	8.6	41	2.9	0	5.1	0.8	1.1	0	4.7	100
Average [b]	0.7	6.6	5.0	8.6	41	2.9	0	5.1	0.8	1.1	0	4.7	100

a Complete courses of treatment.
b Overall averages for sample calculated as total number of each particular type of treatment divided by total number of all treatments.

Table 54
Percentage contributions by disease category to annual total numbers of brachytherapy treatments [a] (1991-1996)
Based on data and qualifications from Table 52

Country / area	*Head/neck tumour*	*Breast tumour*	*Gynaecological tumour*	*Prostate tumour*	*Total of all brachytherapy treatments*
Health-care level I					
Australia	2.1	3.8	86	0	100
Belarus	22	3.7	61	1.4	100
Canada	1.9	0	79	12	100
Croatia	0	0	100	0	100
Cyprus	0	0	100	0	100
Czech Republic	0.6	3.7	91	0.2	100
Ecuador	0	0	100	0	100
Ireland	4.4	0.9	88	-	100
Kuwait	0	0	100	0	100
Netherlands	7.9	59	26	2.4	100
New Zealand	11	4.7	75	0	100
Panama	2.8	0	97	0	100
Romania	1.2	2.5	88	0.4	100
Slovakia	3.9	21	59	0.2	100
Slovenia	32	0	63	0.7	100
Sweden	-	-	100	-	100
United Arab Emirates	23	0	77	0	100
Average [b]	4.3	10	78	2.2	100
Health-care level II					
Mexico	1.0	1.8	0.4	0	100
Pakistan	0	0	96	0	100
Peru	0	0	100	0	100
Tunisia	13	0	63	0	100
Turkey	8.6	4.9	75	-	100
Average [b]	4.5	2.8	52	0	100
Health-care level III					
Morocco	-	-	100	-	100
Sudan	0	0	100	-	100
Average [b]	0	0	100	-	100

a Complete courses of treatment.
b Overall averages for sample calculated as total number of each particular type of treatment divided by total number of all treatments.

Table 55
Distribution by age and sex of patients undergoing teletherapy treatment for a range of conditions (1991-1996)
Data from UNSCEAR Survey of Medical Radiation Usage and Exposures

Health-care level	*Country / area*	*Age distribution (%)*			*Sex distribution (%)*	
		0–15 years	*16–40 years*	*>40 years*	*Male*	*Female*
Leukaemia						
I	Australia	22	18	60	71	29
	Belarus	0	0	100	80	20
	Bulgaria	100	0	0	68	32
	Canada	67	33	0	–	–
	Croatia	0	0	100	0	100
	Cyprus	100	0	0	50	50
	Czech Republic	96	4	0	60	40
	Ecuador	63	34	3	54	46
	Ireland	18	36	45	45	55
	Kuwait	77	23	0	58	42
	New Zealand	36	23	41	62	38
	Panama	40	47	13	67	33
	Romania	5	48	47	50	50
	Slovakia	66	17	17	83	17
	Slovenia	23	26	51	65	35
	United Arab Emirates	62	19	19	88	12
	Average	38	21	41	68	32
II	Jordan	26	38	36	69	31
	Libyan Arab Jamahiriya	73	18	9	64	36
	Mexico	65	20	15	61	39
	Pakistan	41	37	22	66	34
	Peru	55	32	13	18	82
	Turkey	53	37	10	80	20
	Average	52	34	14	72	28
III	Madagascar	100	0	0	50	50
	Morocco	80	–	–	–	–
	Sudan	80	11	9	51	49
	Average	80	11	9	51	49
IV	United Republic of Tanzania	67	11	22	70	30
Lymphoma						
I	Australia	2	21	77	50	50
	Belarus	10	67	23	50	50
	Bulgaria	48	11	41	57	43
	Croatia	3	48	49	55	45
	Cyprus	0	25	75	42	58
	Czech Republic	6	28	66	53	47
	Ecuador	6	39	55	54	46
	Ireland	1	20	78	48	52
	Japan	13	23	64	–	–
	Kuwait	19	31	50	54	46
	Netherlands	–	–	–	55	45
	New Zealand	1	31	68	58	42
	Panama	0	25	75	33	67
	Romania	20	32	48	61	39
	Slovakia	3	20	77	55	45
	Slovenia	5	55	40	57	43
	United Arab Emirates	20	48	32	68	32
	Average	10	26	64	53	47
II	Jordan	13	43	44	68	32
	Libyan Arab Jamahiriya	31	49	20	62	38
	Mexico	3	42	55	57	43
	Pakistan	16	42	42	67	33
	Peru	11	29	60	52	48
	Turkey	26	28	46	60	40

Table 55 (continued)

Health-care level	*Country / area*	*Age distribution (%)*			*Sex distribution (%)*	
		0–15 years	*16–40 years*	*>40 years*	*Male*	*Female*
II	Average	19	34	47	61	39
III	Madagascar	0	60	40	60	40
	Morocco	10	80	10	–	–
	Sudan	14	27	59	64	36
	Average	7	43	50	62	38
IV	United Rep. of Tanzania	30	50	20	62	38
Breast tumour						
I	Australia	0	14	86	0.5	99.5
	Belarus	0	16	84	1.5	98.5
	Bulgaria	0	12	88	0.5	99.5
	Canada	0	16	84	1	99
	Croatia	0	6	94	1	99
	Cyprus	–	–	–	2	98
	Czech Republic	0	5	95	0	100
	Ecuador	0	19	81	1	99
	Ireland	0	8	92	16	84
	Kuwait	0	30	70	0	100
	Netherlands	–	–	–	0.3	99.7
	New Zealand	0	23	77	1	99
	Panama	0	16	84	0	100
	Romania	0	16	84	1.5	98.5
	Slovakia	0	10	90	1	99
	Slovenia	0	10	90	1	99
	United Arab Emirates	0	19	81	9	91
	Average	0	13	87	1.2	98.8
II	Jordan	0	23	77	4	96
	Libyan Arab Jamahiriya	0	31	69	6	94
	Mexico	0	30	70	0.3	99.7
	Pakistan	0	41	59	7	93
	Peru	0	31	69	0	100
	Turkey	0	26	74	2	98
	Average	0	29	71	2	98
III	Madagascar	0	34	66	1	99
	Morocco	–	80	–	–	–
	Sudan	0	40	60	3	97
	Average	0	37	63	2	98
IV	United Rep. of Tanzania	0	2	98	3	97
Lung/thorax tumour						
I	Australia	0	6	94	72	28
	Belarus	0	4	96	94	6
	Bulgaria	0	2	98	94	6
	Canada	0	3	97	61	39
	Croatia	0	1	99	83	17
	Cyprus	0	0	100	80	20
	Czech Republic	0	1	99	87	13
	Ecuador	14	9	77	50	50
	Ireland	0	1	99	66	33
	Japan	0	5	95	–	–
	Kuwait	0	8	92	92	8
	Netherlands	–	–	–	80	20
	New Zealand	0	2	98	68	32
	Panama	0	0	100	69	31
	Romania	1	8	91	85	15
	Slovakia	0	2	98	88	12
	Slovenia	0	3	97	70	30
	United Arab Emirates	0	2	98	80	20
	Average	0	4	96	72	28

Table 55 (continued)

Health-care level	*Country / area*	*Age distribution (%)*			*Sex distribution (%)*	
		0–15 years	*16–40 years*	*>40 years*	*Male*	*Female*
II	Jordan	2	10	88	86	14
	Libyan Arab Jamahiriya	1	13	86	86	14
	Mexico	0	11	89	70	30
	Pakistan	1	28	71	65	35
	Peru	0	11	89	76	24
	Turkey	0	8	92	95	5
	Average	0	11	89	88	12
III	Madagascar	0	45	55	90	10
IV	United Rep. of Tanzania	0	0	100	76	24
Gynaecological tumour						
I	Australia	0	11	89	0	100
	Belarus	0	12	88	0	100
	Bulgaria	0	18	82	0	100
	Canada	0	17	83	0	100
	Croatia	0	15	85	0	100
	Cyprus	0	17	83	0	100
	Czech Republic	0	11	89	0	100
	Ecuador	0	18	82	0	100
	Ireland	0	10	89	1	99
	Japan	0	12	88	0	100
	Kuwait	0	37	63	0	100
	Netherlands	–	–	–	0	100
	New Zealand	1	30	69	0	100
	Panama	0	25	75	0	100
	Romania	1	27	72	0	100
	Slovakia	0	20	80	0	100
	Slovenia	0	32	68	0	100
	United Arab Emirates	0	18	82	0	100
	Average	0	15	85	0	100
II	Jordan	0	23	77	0	100
	Libyan Arab Jamahiriya	0	24	76	0	100
	Mexico	0	34	66	0	100
	Pakistan	2	48	50	0	100
	Peru	1	21	78	0	100
	Turkey	4	8	88	0	100
	Average	2	25	73	0	100
III	Madagascar	1	45	54	0	100
	Sudan	0	23	77	0	100
	Average	1	37	62	0	100
IV	United Republic of Tanzania	0	40	60	0	100
Head/neck tumour						
I	Australia	0	9	91	75	25
	Belarus	3	8	89	79	21
	Bulgaria	1	6	93	81	19
	Canada	0	11	89	66	34
	Croatia	0	4	96	87	13
	Cyprus	0	0	100	80	20
	Czech Republic	0	4	96	73	27
	Ecuador	3	10	87	43	57
	Ireland	1	4	95	67	33
	Japan	0	10	90	–	–
	Kuwait	0	35	65	56	44
	Netherlands	–	–	–	75	25
	New Zealand	0	19	81	63	37
	Panama	4	4	92	69	31
	Romania	3	15	82	79	21
	Slovakia	0	6	94	87	13

Table 55 (continued)

Health-care level	*Country / area*	*Age distribution (%)*			*Sex distribution (%)*	
		0–15 years	*16–40 years*	*>40 years*	*Male*	*Female*
I	Slovenia	1	16	83	88	12
	United Arab Emirates	0	34	66	72	28
	Average	0	10	90	75	25
II	Jordan	10	10	80	76	24
	Libyan Arab Jamahiriya	4	17	79	74	26
	Mexico	0	18	82	96	4
	Pakistan	3	37	60	58	42
	Peru	0	27	73	48	52
	Turkey	4	20	76	76	24
	Average	3	23	74	76	24
III	Madagascar	0	35	65	91	9
	Morocco	10	–	–	–	–
	Sudan	4	17	79	66	34
	Average	1	30	69	83	17
IV	United Rep. of Tanzania	0	1	99	44	56
Brain tumour						
I	Australia	3	23	74	63	37
	Belarus	68	21	11	57	43
	Bulgaria	36	4	60	56	44
	Canada	0	8	92	58	42
	Croatia	4	14	82	50	50
	Cyprus	0	0	100	50	50
	Czech Republic	11	21	68	54	46
	Ecuador	28	34	38	51	49
	Ireland	4	2	75	63	27
	Kuwait	12	41	47	47	53
	Netherlands	–	–	–	60	40
	New Zealand	13	32	55	61	39
	Panama	19	26	55	55	45
	Romania	15	37	48	66	34
	Slovakia	7	35	58	61	39
	Slovenia	1	14	85	50	50
	United Arab Emirates	23	23	54	77	23
	Average	8	19	73	59	41
II	Jordan	28	34	38	56	44
	Libyan Arab Jamahiriya	28	25	47	66	34
	Mexico	26	28	46	53	47
	Pakistan	20	46	34	67	33
	Peru	18	33	49	63	37
	Turkey	11	39	50	58	42
	Average	15	37	48	58	42
III	Madagascar	0	50	50	50	50
	Morocco	10	80	10	–	–
	Sudan	0	33	67	67	33
	Average	0	35	65	65	35
Skin tumour						
I	Australia	0	11	89	71	29
	Belarus	0	7	93	40	60
	Bulgaria	0	0	100	75	25
	Canada	0	10	90	60	40
	Croatia	0	5	95	53	47
	Cyprus	0	0	100	50	50
	Czech Republic	0	5	95	75	25
	Ecuador	3	20	77	55	45
	Ireland	0	3	97	59	41
	Japan	2	25	73	–	–

Table 55 (continued)

Health-care level	*Country / area*	*Age distribution (%)*			*Sex distribution (%)*	
		0–15 years	*16–40 years*	*>40 years*	*Male*	*Female*
I	Kuwait	0	0	100	100	0
	Netherlands	-	-	-	65	35
	New Zealand	0	8	92	64	36
	Panama	14	14	72	57	43
	Slovakia	0	4	96	50	50
	Slovenia	0	7	93	65	35
	United Arab Emirates	10	10	80	90	10
	Average	1	18	81	63	37
II	Jordan	6	6	88	67	33
	Libyan Arab Jamahiriya	8	20	72	50	50
	Mexico	1	12	87	52	48
	Pakistan	6	32	62	70	30
	Peru	0	18	82	53	47
	Turkey	0	18	82	69	31
	Average	3	22	75	64	36
III	Madagascar	0	40	60	60	40
	Morocco	0	100	0	–	–
	Sudan	4	29	67	–	–
	Average	2	34	64	60	40
IV	United Rep. of Tanzania	0	80	20	63	37
Bladder tumour						
I	Australia	0	8	92	67	33
	Belarus	0	3	97	74	26
	Bulgaria	0	0	100	75	25
	Canada	0	6	94	66	34
	Croatia	0	0	100	69	31
	Cyprus	0	0	100	80	20
	Czech Republic	0	1	99	53	47
	Ecuador	0	0	100	85	15
	Ireland	0	0	100	100	0
	Japan	0	13	87	–	–
	Kuwait	0	18	82	73	27
	Netherlands	–	–	–	80	20
	New Zealand	0	1	99	73	27
	Panama	0	0	100	50	50
	Romania	0	0	100	80	20
	Slovakia	0	0	100	92	8
	Slovenia	0	0	100	54	46
	United Arab Emirates	0	4	96	88	12
	Average	0	9	91	75	25
II	Jordan	0	0	100	93	7
	Libyan Arab Jamahiriya	0	6	94	88	12
	Mexico	0	12	88	64	36
	Pakistan	1	31	68	75	25
	Peru	0	9	91	70	30
	Turkey	0	2	98	91	9
	Average	0	10	90	84	16
III	Madagascar	0	50	50	60	40
	Morocco	0	100	0	–	–
	Sudan	0	7	93	70	30
	Average	0	11	89	69	31
IV	United Rep. of Tanzania	0	80	20	64	36
Prostate tumour						
I	Australia	0	12	88	100	0
	Belarus	3	0	97	100	0

Table 55 (continued)

Health-care level	*Country / area*	*Age distribution (%)*			*Sex distribution (%)*	
		0–15 years	*16–40 years*	*>40 years*	*Male*	*Female*
I	Canada	0	0	100	100	0
	Croatia	0	0	100	100	0
	Cyprus	0	0	100	100	0
	Czech Republic	0	0	100	100	0
	Ecuador	0	0	100	100	0
	Ireland	0	0	100	100	0
	Kuwait	0	0	100	100	0
	New Zealand	0	1	99	100	0
	Panama	0	0	100	100	0
	Romania	0	12	88	100	0
	Slovakia	0	0	100	100	0
	Slovenia	0	5	95	100	0
	United Arab Emirates	0	0	100	100	0
	Average	0	4	96	100	0
II	Jordan	0	0	100	100	0
	Libyan Arab Jamahiriya	0	10	90	100	0
	Mexico	0	5	95	100	0
	Pakistan	0	19	81	100	0
	Peru	0	4	96	100	0
	Turkey	0	0	100	100	0
	Average	0	6	94	100	0
III	Madagascar	0	0	100	100	0
IV	United Rep. of Tanzania	0	1	99	100	0
Tumour of the rectum						
I	Australia	0	6	94	70	30
	Belarus	0	8	92	49	51
	Bulgaria	0	5	95	81	19
	Canada	0	11	89	47	53
	Croatia	0	10	90	42	58
	Cyprus	0	0	100	75	25
	Czech Republic	0	2	98	59	41
	Ecuador	0	13	87	44	56
	Ireland	0	2	98	73	27
	Japan	0	5	95	–	–
	Kuwait	0	25	75	67	33
	Netherlands	–	–	–	55	45
	New Zealand	0	10	90	58	42
	Panama	0	0	100	48	52
	Romania	0	7	93	59	41
	Slovakia	0	5	95	61	39
	Slovenia	0	8	92	70	30
	United Arab Emirates	0	20	80	73	27
	Average	0	6	94	57	43
II	Jordan	0	22	78	47	53
	Libyan Arab Jamahiriya	0	35	65	67	33
	Mexico	0	16	84	63	37
	Pakistan	1	36	63	71	29
	Peru	0	13	87	62	38
	Turkey	1	16	83	66	34
	Average	1	19	80	65	35
III	Madagascar	0	33	67	55	45
	Sudan	5	35	60	54	46
	Average	2	34	64	55	45
Benign disease						
I	Australia	1	23	76	43	57
	Bulgaria	2	13	85	34	66
	Croatia	0	75	25	50	50

Table 55 (continued)

Health-care level	*Country / area*	*Age distribution (%)*			*Sex distribution (%)*	
		0–15 years	*16–40 years*	*>40 years*	*Male*	*Female*
I	Cyprus	0	100	0	50	50
	Czech Republic	0	0	100	40	60
	Ecuador	100	0	0	100	0
	Japan	4	37	59	–	–
	New Zealand	0	39	61	47	53
	Panama	0	50	50	25	75
	Romania	10	80	10	20	80
	Slovenia	0	0	100	50	50
	United Arab Emirates	14	14	72	57	43
	Average	0	1	99	40	60
II	Jordan	0	48	52	40	60
	Mexico	5	43	52	43	57
	Pakistan	5	54	41	75	25
	Turkey	4	23	73	45	55
	Average	4	39	57	50	50
III	Madagascar	0	60	40	50	50
IV	United Rep. of Tanzania	2	80	18	36	64
Other						
I	Australia (digestive)	0	8	92	75	25
	Cyprus (brain mets.)	0	0	100	80	20
	Cyprus (bone mets.)	0	0	100	60	40
	Czech Republic (colon)	0	1	99	51	49
II	Turkey (opthalmopathy)	37	15	48	69	31
IV	United Republic of Tanzania (Kaposis sarc.)	0	50	50	68	32
All teletherapy treatments						
I	Australia	2	13	85	58	42
	Belarus	4	14	82	48	52
	Bulgaria	6	12	82	30	70
	Croatia	0	9	91	35	65
	Ecuador	7	19	74	25	75
	Ireland	–	–	–	58	42
	Kuwait	9	28	63	45	55
	Netherlands	0	7	93	44	56
	New Zealand	1	14	85	52	48
	Slovakia	1	11	88	45	55
	Sweden	1	8	91	–	–
	United Arab Emirates	5	19	76	55	45
	Average	1	11	88	49	51
II	Jordan	8	24	68	52	48
	Libyan Arab Jamahiriya	10	22	68	61	39
	Mexico	4	26	70	37	63
	Pakistan	8	37	55	60	40
	Average	6	30	64	47	53

The entries in this Table are qualified as follows:

Australia: Survey data from only 8 of 31 radiotherapy treatment centres (representing about 42% of national practice).
Canada: On the basis of data from the Nova Scotia Cancer Treatment and Research Foundation and the province of Manitoba (collectively representing about 8% of the population).
Croatia: Data from one large centre serving about one-fifth of population.
Jordan: Survey data from one hospital.
New Zealand: Data from 50% of radiotherapy centres (serving about two-thirds of population).
Peru: Survey data from INEN (Cancer Institute, Lima, serving population of about 7 million).
United Republic of Tanzania: Data for 'Lung/thorax tumour' include treatments of the oesophagus.
Turkey: Survey data from Hacettepe University Hospital, Çukurova University Hospital, Istanbul University Hospital, Cerrahpaşa Hospital and Gülhane Military Hospital.

Table 56
Distribution by age and sex of patients undergoing brachytherapy treatment for a range of conditions (1991-1996)
Data from UNSCEAR Survey of Medical Radiation Usage and Exposures

Health-care level	*Country*	*Age distribution (%)*			*Sex distribution (%)*	
		0–15 years	*16–40 years*	*>40 years*	*Male*	*Female*
Head/neck tumour						
I	Australia	0	0	100	59	41
	Belarus	0	11	89	70	30
	Czech Republic	0	4	96	73	27
	Ireland	0	0	100	60	40
	Panama	0	25	75	25	75
	Slovakia	0	24	76	81	19
	Slovenia	1	20	79	25	75
	United Arab Emirates	0	20	80	80	20
	Average	0	14	86	61	39
II	Mexico	0	5	95	85	15
	Turkey	0	30	70	84	16
	Average	0	28	72	84	16
III	Morocco	10	–	–	–	–
Breast tumour						
I	Australia	0	0	100	0	100
	Belarus	0	17	83	0	100
	Czech Republic	0	5	95	0	100
	Ireland	0	0	100	0	100
	Slovakia	0	20	80	0	100
	Average	0	15	85	0	100
II	Mexico	0	34	66	0	100
	Turkey	0	24	76	3	97
	Average	0	26	74	2	98
Gynaecological tumour						
I	Australia	0	9	91	0	100
	Belarus	0	10	90	0	100
	Canada	0	13	87	0	100
	Croatia	0	10	90	0	100
	Cyprus	0	17	83	0	100
	Czech Republic	0	11	89	0	100
	Ecuador	0	12	88	0	100
	Ireland	0	0	100	0	100
	Kuwait	0	30	70	0	100
	Panama	0	25	75	0	100
	Slovakia	0	13	87	0	100
	Slovenia	0	6	94	0	100
	United Arab Emirates	0	24	76	0	100
	Average	0	11	89	0	100
II	Mexico	0	48	52	0	100
	Pakistan	0	52	48	0	100
	Peru	0	20	80	0	100
	Turkey	0	2	98	0	100
	Average	0	10	90	0	100
III	Sudan	0	60	40	0	100
Prostate tumour						
I	Belarus	0	0	100	100	0
	Canada	0	0	100	100	0
	Czech Republic	0	0	100	100	0

Table 56 (continued)

Health-care level	*Country*	*Age distribution (%)*			*Sex distribution (%)*	
		0–15 years	*16–40 years*	*>40 years*	*Male*	*Female*
I	Slovakia	0	0	100	100	0
	Slovenia	0	0	100	100	0
	Average	0	0	100	100	0
Other brachytherapy treatments						
I	Australia (bile duct)	0	0	100	88	12
	Australia (oesophagus)	0	6	94	50	50
	Czech Republic (bronchus)	0	3	97	87	13
	Czech Republic (skin)	0	5	95	75	25
	Ireland (oesophagus)	0	0	100	–	–
	Ireland (rectum)	0	0	100	–	–
	Slovakia (bronchus)	0	6	94	89	11
	Slovakia (GI tract)	0	4	96	100	0
II	Turkey (genitals)	0	3	97	100	0
All brachytherapy treatments						
I	Australia	0	5	95	42	58
	Belarus	0	13	87	22	78
	Bulgaria	0.5	8	91.5	36	64
	Croatia	0	10	90	0	100
	Ecuador	0	12	88	0	100
	Ireland	0	0	100	20	80
	Kuwait	0	30	70	0	100
	Slovakia	0	14	86	18	82
	United Arab Emirates	0	23	77	18	82
	Average	0	9	91	30	70
II	Mexico	0	49	51	3	97
	Pakistan	0	65	35	38	62
	Average	0	50	50	6	94

The entries in this Table are qualified as follows:

Australia: Survey data from only 8 of 31 radiotherapy treatment centres (representing about 42% of national practice).
Canada: On the basis of data from the Nova Scotia Cancer Treatment and Research Foundation and the province of Manitoba (collectively representing about 8% of the population).
Croatia: Data from one large centre serving about one-fifth of population.
New Zealand: Data from 50% of radiotherapy centres (serving about two-thirds of population).
Peru: Survey data from INEN (Cancer Institute, Lima, serving population of about 7 million).
Turkey: Survey data from Hacettepe University Hospital, Çukurova University Hospital, Istanbul University Hospital, Cerrahpaşa Hospital and Gülhane Military Hospital.

Table 57
Prescribed doses to patients undergoing radiation teletherapy by disease category (1991-1996)
Data from UNSCEAR Survey of Medical Radiation Usage and Exposures unless otherwise indicated

Country / area	*Typical dose [a] to target volume (Gy)*											
	Leukaemia	*Lymphoma*	*Breast tumour*	*Lung/thorax tumour*	*Gynaecolo-gical tumour*	*Head/neck tumour*	*Brain tumour*	*Skin tumour*	*Bladder tumour*	*Prostate tumour*	*Tumour of rectum*	*Benign disease*
Health-care level I												
Argentina	14 (10–20)	36 (25–45)	60 (55–65)	66 (45–70)	50 (45–60)	70 (45–75)	65 (40–65)	75 (60–78)	58 (50–64)	70 (50–76)	55 (45–60)	(15–75)
Australia	15 (11–22)	34 (17–46)	53 (26–64)	44 (22–63)	49 (32–57)	56 (28–67)	50 (29–58)	45 (25–62)	49 (27–62)	52 (33–62)	49 (26–54)	15 (6–26)
Belarus	30 (20–40)	40 (30–46)	50 (30–70)	60 (40–70)	40 (40–60)	60 (40–70)	60 (40–70)	65 (60–70)	60 (40–60)	60 (40–60)	75 (40–80)	–
Bulgaria	24 (24–30)	36 (36–44)	50 (40–60)	56 (40–60)	56 (50–60)	60 (60–70)	55 (50–60)	60 (50–70)	60 (50–70)	60 (50–70)	60 (50–70)	5 (1–50)
Canada	25 (12–30)	40 (20–50)	50 (40–60)	40 (17–60)	45 (25–70)	60 (50–70)	50 (20–60)	35 (20–50)	50 (20–70)	60 (50–66)	50 (40–60)	(6–20)
Croatia	30	48 (40–55)	52 (50–60)	60 (52–68)	60 (52–65)	60 (60–70)	60 (50–66)	60 (60–70)	60 (54–66)	60 (60–65)	55 (55–65)	15 (8–40)
Cyprus	18	40 (35–45)	50	(20–60)	45 (45–50)	60 (20–70)	60	50	66 (20–66)	64	54	12 (6–18)
Czech Republic	12 (12–24)	30 (30–40)	50 (50–60)	55 (50–60)	60 (45–65)	60 (45–65)	60 (45–65)	55 (50–60)	60 (55–60)	65 (60–70)	50 (45–60)	6 (4–8)
Denmark	12	40 (35–40)	48 (48–58)	(30–50)	46 [c]	64 (62–68)	54	48	60	–	46 [d]	–
Ecuador	25 (±25%)	40 (±10%)	60 (±16%)	50 (±10%)	50 ((±30%)	50 (±20%)	40 (±30%)	50 (12–72)	50 (±20%)	50 (±10%)	50 ((±20%)	30
Hungary	–	–	–	–	–	–	–	–	–	–	–	4 (1–5)
Ireland	30 (25–30)	(30–60)	45 (40–50)	(40–55)	40	60 (40–66)	40	35 (35–50)	60 (60–70)	66 (66–70)	50 (45–50)	–
Kuwait	18 (18–24)	36 (30–40)	50 (50–65)	60 (55–60)	46 (40–46)	60 (60–66)	60 (55–60)	40 (30–40)	60 (60–64)	60 (60–66)	50 (50–54)	–
Netherlands	–	40 (40–48)	66 (64–68)	64 (60–68)	46 (42–48)	66 (64–70)	60 (60–64)	60 (60–64)	60 (60–64)	–	(45–60)	–
New Zealand	15 (6–28)	40 (8–50)	50 (8–65)	50 (8–60)	45 (27–65)	60 (40–70)	50 (20–66)	40 (18–64)	60 (30–64)	65 (60–68)	45 (18–60)	30 (8–50)
Panama	12 (12–24)	40 (40–45)	50 (50–60)	50 (50–60)	50 (50–70)	60 (60–70)	50 (40–60)	50	50	60 (60–70)	50 (50–60)	15 (15–20)
Romania	(10–40)	(6–45)	–	(2–74)	(18–70)	(2–87)	(16–60)	–	(16–74)	(12–70)	(20–70)	–
Russian Federation	–	(25–60)	(40–70)	(40–70)	(40–60)	(40–70)	–	(40–70)	(40–60)	(40–60)	(40–60)	(0.5–5)
Slovakia	18 (18–24)	36 (35–40)	50 (46–50)	60	60 (60–80)	60 (60–80)	56 (56–60)	60 (60–70)	60	60 (60–66)	50 (50–60)	4 (4–20)
Slovenia	5 (5–12)	30 (20–40)	50 (50–60)	50 (30–60)	50 (50–60)	60 (50–70)	40 (30–50)	60 (50–70)	50 (40–60)	50 (20–60)	50 (20–60)	20 (20–50)
Sweden	–	37 (26 [b])	49 (35 [b])	51 (34 [b])	55 (35 [b])	59 (37 [b])	52 (37 [b])	46 (31 [b])	48 (31 [b])	64 (35 [b])	38 (36 [b])	–
United Arab Emirates	12 (12–24)	40 (35–44)	50 (45–65)	60 (50–60)	45 (40–60)	66 (60–66)	54 (50–60)	50 (50–64)	64 (60–64)	64 (60–66)	45 (40–60)	30 (30–45)
United States [I23]	–	–	(45–50)	–	–	–	–	–	–	(60–72)	–	–
Average	17	39	54	49	50	60	53	48	57	59	49	6
Health–care level II												
Jordan	20 (6–24)	35 (25–40)	50 (42–50)	30 (20–60)	44 (30–50)	60 (40–66)	50 (30–60)	50 (40–55)	66 (30–66)	60 (30–60)	50 (30–50)	10 (10–40)
Libyan Arab Jamahiriya	18 (18–24)	45 (45–50)	50 (50–60)	30 (30–60)	50 (50–60)	66 (60–66)	55 (50–60)	45 (45–50)	60 (60–65)	65 (60–65)	60 (50–60)	–
Mexico	24 (18–24)	40 (35–45)	50 (50–65)	55 (50–65)	80 (50–80)	75 (50–75)	65 (55–65)	65 (55–65)	65 (65–70)	65 (65–70)	65 (65–70)	24 (24–32)
Peru	18 (18–30)	44 (30–50)	60 (45–60)	50 (30–60)	50 (45–55)	60 (50–75)	60 (30–70)	50 (45–55)	60 (55–65)	70 (60–72)	50 (45–55)	–
Tunisia	35	(45–55)	50 (50–75)	(45–65)	(20–60)	75 (55–75)	55	(65–75)	65 (55–65)	65 (55–65)	(35–65)	20
Turkey	22 (10–30)	34 (20–58)	50 (45–70)	59 (45–66)	51 (45–62)	63 (50–70)	55 (45–60)	58 (40–70)	61 (50–66)	61 (50–60)	50 (40–60)	14 (9–25)
Average	22	36	50	57	63	67	57	60	62	64	53	18

Table 57 (continued)

Country	*Typical dose to target volume (Gy)*											
	Leukaemia	*Lymphoma*	*Breast tumour*	*Lung/thorax tumour*	*Gynaecolo-gical tumour*	*Head/neck tumour*	*Brain tumour*	*Skin tumour*	*Bladder tumour*	*Prostate tumour*	*Tumour of rectum*	*Benign disease*
Health-care level III												
Madagascar	24	40	45	45	45	45	45	50	50	45	45	–
Morocco	24 (18-24)	36 (36-40)	50	(30-70)	46	70	60	70	70	70	(50-70)	–
Sudan	30 (20-30)	50 (40-50)	45	45 (40-50)	55 (50-60)	55 (50-60)	–	55 (50-60)	55 (50-60)	25 (20-30)	45 (40-50)	25 (20-30)
Average	29	45	45	45	49	48	45	53	54	45	45	25
Health-care level IV												
United Rep. of Tanzania	30 (20-30)	30 (20-30)	50 (30-50)	30 (30-45)	64 (30-64)	60 (30-60)	45 (30-45)	60 (30-60)	60 (30-60)	60 (30-60)	60 (30-60)	6

a Prescribed dose for complete course of treatment. Range or standard deviation in parentheses. Mean doses for each health-care level are frequency-weighted averages of national values. These doses should not be used to infer deterministic or stochastic risks since these depend *inter alia* strongly on irradiation technique (dose distribution) and fractionation.
b Palliative treatment.
c Plus brachytherapy.
d Plus boost.

The entries in this Table are qualified as follows:

Argentina: On the basis of data from one large national centre.
Australia: Survey data from only 8 of 31 radiotherapy treatment centres (representing about 42% of national practice).
Canada: On the basis of data from the Nova Scotia Cancer Treatment and Research Foundation and the province of Manitoba (collectively representing about 8% of the population).
Croatia: Data from one large centre serving about one-fifth of population.
Cyprus: Target dose of 50 Gy for breast tumour refers to treatment with ^{60}Co unit; this is supplemented by treatment with x rays (target dose of 14 Gy); target dose of 45 Gy for gynaecological tumour refers to treatment with ^{60}Co unit; this is supplemented by treatment with x rays (target dose of 15 Gy).
Jordan: Survey data from one hospital.
Madagascar: Treatments shown for Breast, Lung/thorax, Gynaecological, Head/neck, Brain, Skin, Bladder, Prostate and Rectum tumours supplemented by additional irradiation with x rays.
New Zealand: Data from 50% of radiotherapy centres (serving about two thirds of population).
Peru: Survey data from INEN (Cancer Institute, Lima, serving population of about 7 million).
United Republic of Tanzania: Data for 'Lung/thorax tumour' include treatments of the oesophagus.
Turkey: Survey data from Hacettepe University Hospital, Çukurova University Hospital, Istanbul University Hospital, Cerrahpaşa Hospital, and Gülhane Military Hospital.
United Arab Emirates: Doses for radical treatments only.
United States: Breast tumours receive an additional 10-20 Gy "boost" with either electrons or brachytherapy.

Table 58
Prescribed doses to patients undergoing radiation brachytherapy by disease category (1991-1996)
Data from UNSCEAR Survey of Medical Radiation Usage and Exposures unless otherwise indicated

Country / area	*Typical dose [a] to target volume (Gy)*			
	Head/neck tumour	*Breast tumour*	*Gynaecological tumour*	*Prostate tumour*
Health-care level I				
Argentina	75 (68–78)	–	60 (50–65)	70
Australia	30 (22–45)	10 (10–25)	32 (15–42)	–
Belarus	40 (30–50)	40 (30–40)	45 (30–50)	40 (30–60)
Bulgaria	60 (60–70)	40 (30–40)	70 (30–70)	–
Canada	60	–	45 (11–50)	30 (25–40)
Cyprus	–	–	30	–
Czech Republic	65 (60–70)	12 (10–12)	60 (60–70)	65 (60–70)
Denmark	–	–	35 (plus teletherapy)	–
Ecuador	–	–	35 (±15%)	–
Ireland	30 (30–60)	30	15 (10–20)	–
Kuwait	–	–	36 (30–36)	–
Netherlands	60 (20–30 boost)	(20–24)	(30–60)	60
New Zealand	45 (25–65)	15	70 (15–70)	–
Panama	20 (20–30)	–	20 (20–30)	–
Russia	(30–50)	(20–40)	(20–40)	–
Slovakia	20 (20–30)	15	30 (10–60)	–
Slovenia	–	–	–	–
United Arab Emirates	10 (5–10)	–	20 (15–20)	–
Average	44	16	45	35
Health–care level II				
Mexico	30 (20–40)	15 (10–20)	30 (20–30)	–
Peru	–	–	40 (30–80)	–
Tunisia	(55–75)	–	(20–60)	–
Turkey	21 (18–40)	20 (20–25)	24 (16–24)	–
Average	22	19	29	–
Health–care level III				
Morocco	24	–	24	–
Sudan	–	–	35 (30–40)	–
Average	24	–	24	–

a Prescribed dose for complete treatment. Range or standard deviation in parentheses. Mean doses for each health-care level are frequency-weighted averages of national values. These doses should not be used to infer deterministic or stochastic risks since these depend *inter alia* strongly on irradiation technique (dose distribution) and fractionation.

The entries in this Table are qualified as follows:

Argentina: On the basis of data from one large national centre.
Australia: Survey data from only 8 of 31 radiotherapy treatment centres (representing about 42% of national practice).
Canada: On the basis of data from the Nova Scotia Cancer Treatment and Research Foundation and the province of Manitoba (collectively representing about 8% of the population).
New Zealand: Data from 50% of radiotherapy centres (serving about two-thirds of population).
Peru: Survey data from INEN (Cancer Institute, Lima, serving population of about 7 million).
Turkey: Survey data from Hacettepe University Hospital, Çukurova University Hospital, Istanbul University Hospital, Cerrahpaşa Hospital, and Gülhane Military Hospital.
United Arab Emirates: Doses for radical treatments only.

Table 59
Gonad doses from photon teletherapy treatments for some specific tumour sites
[V6]

Tumour site/disease	*Treatment technique*	*Target dose [a] (Gy)*	*Gonad dose (mGy)*	
			^{60}Co	*4–25 MV*
Brain	2 lateral opposed beams	20–60	10–40	10–30
Breast	2 tangential beams	50	110–170	20–50
Thorax: lung cancer	AP/PA parallel opposed beams	45–55	50–80	30–50
Thorax: Hodgkin's disease	AP/PA mantle fields	36–40	80–100	60–80

a These doses should not be used to infer deterministic or stochastic risks since these depend *inter alia* strongly on irradiation technique (dose distribution) and fractionation.

Table 60
Annual numbers [a] of treatments per 1,000 population assumed in global model for radiotherapy practice (1991-1996)

Disease/site	*Level I*	*Level II*	*Level III*	*Level IV*	*World*	*Contribution to world total (%)*
Teletherapy						
Leukaemia	0.01	0.04	0.01	0.0004	0.021	3
Lymphoma	0.06	0.04	0.03	0.003	0.042	5
Breast tumour	0.35	0.12	0.13	0.003	0.17	21
Lung/thorax tumour	0.36	0.08	0.02	0.004	0.14	17
Gynaecological tumour	0.12	0.10	0.09	0.02	0.09	11
Head/neck tumour	0.06	0.09	0.04	0.001	0.07	8
Brain tumour	0.04	0.05	0.004	0	0.04	5
Skin tumour	0.05	0.02	0.01	0.003	0.02	3
Bladder tumour	0.04	0.02	0.01	0.0004	0.02	2
Prostate tumour	0.18	0.02	0.01	0.0005	0.06	7
Tumour of rectum	0.07	0.02	0.01	0	0.03	4
Benign disease	0.09	0.01	0.02	0.002	0.03	3
Other	0.09	0.10	0.10	0.01	0.09	11
Total	1.5	0.69	0.47	0.05	0.82	100
Brachytherapy						
Head/neck tumour	0.01	0.001	0		0.003	4
Breast tumour	0.02	0.0005	0		0.006	9
Gynaecological tumour	0.16	0.009	0.015		0.05	75
Prostate tumour	0.004	0	0		0.001	2
Other	0.01	0.007	0		0.007	10
Total	0.20	0.02	0.02		0.07	100

a Estimated on the basis of average percentage distributions by treatment type (Tables 53 and 54) and average total frequencies (Tables 51 and 52) observed for each health-care level.

Table 61
Global resources for high-energy radiation therapy
[D27]

Region	*Number of radiation therapy centres*	*Number of ^{60}Co machines*	*Number of clinical accelerators*	*Teletherapy machines [a] per million population*
North America	1 909	202	2 238	8.1
Central America	139	115	30	1.1
Tropical South America	266	219	122	1.2
Temperate South America	139	128	46	3.2
Caribbean	18	23	1	0.8
Western Europe	1 027	410	1 109	3.9
Eastern Europe	327	491	148	1.6
Northern Africa	59	49	35	0.6
Middle Africa	22	25	3	0.1
Southern Africa	21	19	27	0.8
Middle East	92	64	56	0.5
Indian Subcontinent	221	286	46	0.3
South East Asia	81	71	59	0.3
East Asia	1 107	606	948	1.1
Australia and the Pacific Islands	49	5	113	5.2
The World	5 500	2 700	5 000	1.4

a Cobalt-60 unit or linear accelerator.

Table 62
Temporal trends in annual frequency of radiotherapy treatments [a] per 1,000 population
Data from UNSCEAR Surveys of Medical Radiation Usage and Exposures unless otherwise indicated

Country / area	Teletherapy				Brachytherapy			
	1970 – 1979	1980 – 1984	1985 – 1990	1991 – 1996 [b]	1970 – 1979	1980 – 1984	1985 – 1990	1991 – 1996 [c]
Health-care level I								
Argentina	–	–	–	–	–	–	0.2	–
Australia	2.0	–	1.5	1.8	0.8	–	0.2	0.06
Belarus	–	–	–	0.5	–	–	–	0.1
Bulgaria	–	–	–	0.2	–	–	–	0.6
Canada	–	1.6	2.9	1.7	–	–	–	0.07
Cayman Islands	–	–	–	0	–	–	–	0
Croatia	–	–	–	2.0	–	–	–	0.07
Cuba	–	–	0.2	2.0 [e]	–	–	0.05	–
Cyprus	–	–	–	0.9	–	–	–	0.02
Czechoslovakia	2.9	4.2	2.7	–	0.2	0.1	0.1	–
Czech Republic	–	–	–	3.5	–	–	–	0.3
Denmark	–	–	1.2	1.5	–	–	0.1	–
Ecuador	(0.03)	–	(0.08)	0.1	(0.006)	–	(0.02)	0.01
Finland	–	–	1.2	–	–	–	–	–
France	–	–	–	1.7	–	–	–	–
Hungary	–	–	–	3.7	–	–	–	0.3
Iceland	–	–	1.2	–	–	–	–	–
Ireland	–	–	–	1.6	–	–	–	0.09
Japan	0.7	–	0.7	0.7	0.2	0.2	–	–
Kuwait	–	–	0.2	0.2	–	–	0.06	0.02
Luxembourg	–	–	–	0	–	–	0.07	0
Malta	–	–	–	–	–	–	0.03	–
Netherlands	–	–	1.8	2.2 [f]	–	–	0.1	0.15 [f]
New Zealand	0.4	0.4	0.6	1.7	0.1	0.08	0.07	0.05
Norway	0.5 [d]	–	3.9	–	0.2	–	0.1	–
Panama	–	–	–	0.3	–	–	–	0.05
Qatar	–	–	–	0	–	–	–	0
Romania	–	1.7	6.8	0.5	–	0.06	–	0.2
Russian Federation	(0.6)	(0.7)	(0.8)	1.0	(0.3)	(0.4)	(0.3)	0.4
Slovakia	–	–	–	0.8	–	–	–	0.3
Slovenia	–	–	–	2.4	–	–	–	0.1
Sweden	0.6	–	0.8	1.3	0.3	0.2	0.1	0.1
Switzerland	–	–	1.8	–	–	–	0.1	–
United Arab Emirates	–	–	–	0.2	–	–	–	0.009
United Kingdom	–	2.4 [d]	–	2.3	–	–	–	–
United States [I23]	(1.5)	(1.7)	(1.9)	2.0	–	–	–	0.1
Uruguay	–	–	–	1.5 [e]	–	–	–	0
Venezuela	–	–	–	1.6 [e]	–	–	–	–
Yugoslavia	–	–	0.6	–	–	–	0.9	–
Average	1.0	2.4 [d]	1.2	1.5	0.26	0.17	0.24	0.2
Health-care level II								
Antigua and Barbuda	–	–	–	0	–	–	–	0
Bahamas	–	–	–	0	–	–	–	0
Barbados	–	–	0.6	3.1 [e]	–	–	0.2	–
Belize	–	–	–	0	–	–	–	0
Bolivia	–	–	–	0.8 [e]	–	–	–	–
Brazil	–	–	–	1.3	–	–	–	–
Chile	–	–	–	2.1 [e]	–	–	–	–
China	–	–	0.2	–	–	–	0.08	–
Colombia	–	–	–	1.6 [e]	–	–	–	–
Dominica	–	–	–	0	–	–	–	0
Dominican Republic	–	–	–	1.9 [e]	–	–	–	–
El Salvador	–	–	–	2.0 [e]	–	–	–	–
Grenada	–	–	–	0	–	–	–	0
Honduras	–	–	–	2.0 [e]	–	–	–	–
India	(0.07)	–	0.1	–	(0.02)	–	0.03	–
Iraq	–	–	0.1	–	–	–	0.009	–
Jordan	–	–	–	0.3	–	–	–	–
Libyan Arab Jamahiriya	–	–	–	0.08	–	–	–	–

Table 62 (continued)

Country / area	*Teletherapy*				*Brachytherapy*			
	1970 – 1979	*1980 – 1984*	*1985 – 1990*	*1991 – 1996* [b]	*1970 – 1979*	*1980 – 1984*	*1985 – 1990*	*1991 – 1996* [c]
Mexico	–	–	–	0.1	–	–	–	0.02
Nicaragua	–	–	–	2.2 [e]	–	–	–	–
Oman	–	–	–	0	–	–	–	0
Pakistan	–	–	–	0.05	–	–	–	0.001
Paraguay	–	–	–	2.2 [e]	–	–	–	0
Peru	0.09	–	0.1	0.1	0.03	–	0.04	0.04
Puerto Rico	–	–	–	1.5 [e]	–	–	–	–
Saint Kitts and Nevis	–	–	–	0	–	–	–	0
Saint Lucia	–	–	–	0	–	–	–	0
Saint Vincent and the Grenadines	–	–	–	0	–	–	–	0
Trinidad and Tobago	–	–	–	1.5 [e]	–	–	–	–
Tunisia	–	–	–	0.1	–	–	–	0.02
Turkey	0.7	0.9	0.7	0.4	–	–	–	0.04
Average	0.1	–	0.2	0.7	0.02	–	0.06	0.02
Health-care level III								
Afghanistan	–	–	–	0	–	–	–	–
Egypt	–	–	0.04	–	–	–	0.0005	–
Guatemala	–	–	–	2.1 [e]	–	–	–	–
Haiti	–	–	–	1.8 [e]	–	–	–	–
Jamaica	–	–	(0.1)	2.1 [e]	–	–	(0.07)	0
Madagascar	–	–	–	0.07	–	–	–	–
Morocco	–	–	–	0.4	–	–	–	0.03
Myanmar	–	0.2	0.2	–	0.01	0.01	0.02	–
Sudan	–	–	0.08	0.05	–	–	0.0003	0.0009
Thailand	–	–	0.09	–	–	0.04	0.04	–
Average	–	–	0.1	0.5	0.02	0.03	0.02	0.02
Health-care level IV								
United Rep. of Tanzania	–	–	–	0.05	–	–	–	–

a Complete course of treatment.
b See qualifications to national data shown in Tables 8 and 51.
c See qualifications to national data shown in Tables 8 and 52.
d Value includes brachytherapy.
e Number of new cancer patients.
f These revised data were received by the Committee after completion of the global analysis.

The entries in this Table are qualified as follows:

Czechoslovakia: Historical data.
Ecuador: Categorized in health-care level II in previous analyses.
India: Categorized in health-care level III for period 1970–1979.
Jamaica: Categorized in health-care level II in previous analyses.
Russian Federation: Historical data were not included in previous analyses.
United States: Historical data from reference [I23] were not included in previous analyses.

Table 63
Temporal trends in the average annual number [a] of the various types of radiotherapy treatments per 1,000 population
Data from UNSCEAR Surveys of Medical Radiation Usage and Exposures

Disease/site	*Period*	*Average annual number of treatments per 1,000 population*			
		Health-care level I	*Health-care level II*	*Health-care level III*	*Health-care level IV*
Teletherapy					
Leukaemia	1970–1979	0.010	0.016	0.0007	–
	1980–1984	0.029	–	0.002	–
	1985–1990	0.018	0.004	0.005	–
	1991–1996	0.005	0.007	0.002	0.0004
Lymphoma	1970–1979	0.038	0.015	0.002	–
	1980–1984	0.025	–	0.004	–
	1985–1990	0.045	0.005	0.007	–
	1991–1996	0.060	0.009	0.003	0.003
Breast tumour	1970–1979	0.12	0.016	0.005	–
	1980–1984	0.13	–	0.012	–
	1985–1990	0.16	0.026	0.018	–
	1991–1996	0.40	0.025	0.014	0.003
Lung/thorax tumour	1970–1979	0.11	0.011	0.002	–
	1980–1984	0.14	–	0.023	–
	1985–1990	0.20	0.025	0.009	–
	1991–1996	0.36	0.015	0.003	0.004
Gynaecological tumour	1970–1979	0.11	0.042	–	–
	1980–1984	0.11	–	0.019	–
	1985–1990	0.16	0.041	0.017	–
	1991–1996	0.11	0.021	0.009	0.020
Benign disease	1970–1979	0.40	–	0.004	–
	1980–1984	2.0	–	–	–
	1985–1990	0.48	0.004	0.004	–
	1991–1996	0.09	0.001	0.002	0.002
Total of all teletherapy	1970–1979	1.0	0.1	–	–
	1980–1984	2.4	–	–	–
	1985–1990	1.2	0.2	0.1	–
	1991–1996	1.5	0.7	0.5	0.050
Brachytherapy					
Breast tumour	1970–1979	0.0001	–	–	–
	1980–1984	–	–	–	–
	1985–1990	0.019	0.012	–	–
	1991–1996	0.011	0.0005	–	–
Prostate	1970–1979	0.0005	–	–	–
	1980–1984	–	–	–	–
	1985–1990	0.005	0.00001	–	–
	1991–1996	0.002	0	–	–
Total of all brachytherapy	1970–1979	0.26	0.02	–	–
	1980–1984	0.17	–	–	–
	1985–1990	0.24	0.06	–	–
	1991–1996	0.20	0.02	0.02	–

a Complete courses of treatment. Overall averages calculated from national data as the total number of treatments divided by the total population for each treatment category. Data for 1991-1996 from Tables 51 and 52; since the total population is not the same for each treatment category due to the lack of comprehensive national data for all countries included in the analysis, these average numbers can not be expected to be additive.

Table 64
Chronology of technical advances in teletherapy
[R4, R7]

Date	*Limitation*	*Development*
1950s	Radiation energy	^{60}Co teletherapy equipment; linear accelerators (LINACs)
1960s	Difficulty in planning	Computer-based treatment planning systems
1970s	Lack of anatomical information	Computed tomography
1980s	Lack of flexibility in field shaping	Multileaf collimators for conformal therapy
Early 1990s	Lack of flexibility in beam intensity	Intensity modulated beams for improved conformal therapy
Late 1990s	Lack of real-time verification	Transit dosimetry from electronic portal imaging devices

Table 65
Estimated annual numbers of radiotherapy treatments [a] in the world 1991-1996

Health-care level	*Population (millions)*	*Annual number of teletherapy tretments*		*Annual number of brachytherapy tretments*		*Annual number of all radiotherapy treatments [b]*	
		Millions	*Per 1,000 population*	*Millions*	*Per 1,000 population*	*Millions*	*Per 1,000 population*
I	1 530	2.3	1.5	0.3	0.2	2.6	1.7
II	3 070	2.1	0.7	0.05	0.02	2.2	0.7
III	640	0.3	0.5	0.01	0.02	0.3	0.5
IV	565	0.03	0.05	0.01 [c]	0.02 [c]	0.04	0.07
World	5 800	4.7	0.8	0.4	0.07	5.1	0.9

a Complete courses of treatment.
b Excluding treatments with radiopharmaceuticals.
c Assumed value in the absence of data.

Table 66
Examples of clinically used radionuclides in cancer therapy
[Z3]

Radionuclide	*Pharmaceutical*	*Clinical use*
^{131}I	NaI	Differentiated thyroid carcinomas
^{32}P	NaH_2PO_4	Polycythaemia vera
^{89}Sr	$SrCl_2$	Bone metastases
^{131}I	mIBG	Neural crest tumours
^{153}Sm	EDTMP	Bone metastases
^{186}Re	HEDP	Bone metastases
^{32}P	$CrPO_4$	Intracavitary
^{90}Y	Microspheres	Hepatic tumours
^{90}Y	Antibodies	Various tumours
^{114m}In	Lymphocytes	Lymphoma
^{131}I	Antibodies	Various tumours
^{131}I	Lipiodol	Hepatic tumours

Table 67
Annual numbers of therapeutic treatments with radiopharmaceuticals per 1,000 population (1991-1996)
Data from UNSCEAR Survey of Medical Radiation Usage and Exposures unless otherwise indicated

Country / area	*Thyroid malignancy* ^{131}I	*Hyper-thyroidism* ^{131}I	*Polycythaemia vera* ^{32}P	*Bone metastases*			*Synovitis* ^{90}Y	*Total number of all treatments*
				^{89}Sr	*Other*	*Total*		
Health-care level I								
Argentina	0.073	0.12	0	0	0	0	0	0.19
Austria [H60]	0.018	0.18	0.0006	–	–	0.0075	[0.0025]	0.29
Bulgaria	0.010	0.0094	0.0015	0	0	0	[0.0092]	0.030
Canada	0.031	0.24	0.0039	0.0047	0	0.0047	0.018	0.30
Cayman Islands	0	0	0	0	0	0	0	0
Croatia	0.014	0.017	0	0	0	0	0	0.031
Cyprus	0.048	0.020	0	0.012	0	0.012	0	0.080
Czech Republic	[0.047]	[0.055]	[0.0009]	–	–	0.044	[0.10]	0.25
Denmark	0.031	0.43	0	0.0012	0	0.0012	0	0.46
Ecuador	0.011	0.022	0	0.0008	0.0009 (^{32}P)	0.0017	0	0.035
Finland [K59]	0.089	0.28	0.050	0.0010	(^{153}Sm, ^{186}Re)	0.011	0.0084	0.44
France [H60]	–	–	–	–	–	0.0091	–	0.13
Germany	0.086	0.27	0.0025	–	^{186}Re	0.0049	0.017	0.39
Greece [H60]	0.047	0.081	–	–	–	0.017	[0.011]	0.16
Hungary	[0.020]	[0.082]	[0.0010]	0	0	0	[0.0019]	0.11
Ireland	0.0083	0.10	0.0069	0.0028	0	0.0028	–	0.12
Israel [H60]	0.0008	–	–	–	–	0.0002	[0.0002]	0.060
Italy	0.054	0.048	0.0011	0	0	0	0	0.11
Japan	0.0073	0.023	–	–	–	–	–	–
Kuwait	0.039	0.091	0	0.0041	0	0.0041	0	0.13
Lithuania	[0.067]	[0.23]	0	0	0	0	0	0.29
Netherlands	0.030	0.19	0.010	–	^{186}Re	0.013	0.020	0.29 [a]
New Zealand [L28]	0.033	0.10	0.012	0.0083	0.0003(^{32}P)	0.0086	0.0046	0.16
Norway [H60]	0.036	0.20	0.0008	–	–	0.016	[0.0010]	0.26
Panama	0.021	–	0	0	0	0	0	–
Portugal [H60]	0.035	0.030	0.0005	–	–	0.0026	[0.0004]	0.068
Qatar	0	0.044	0	0	0	0	0	0.044
Romania	0.050	0.018	0	0	0	0	0	0.068
Russian Federation	–	–	–	–	–	–	–	0.010
Slovakia	0.078	0.035	0	0	0	0	[0.0009]	0.11
Slovenia	0	0.27	0.0010	0.0070	0	0.0070	0.014	0.30
Spain [H60]	–	–	–	–	–	–	–	0.20
Sweden	0.013	0.32	0.034	0.032	0	0.032	0.0014	0.40
Switzerland [H60]	0.028	0.15	0.0017	–	–	0.013	[0.031]	0.27
United Arab Emirates	0.013	0.011	0	0	0	0	0	0.024
United Kingdom [C27]	0.020	0.20	0.012	0.0092	0	0.0092	0.0070	0.25
United States [I23]	0.039	0.19	–	–	–	–	–	–
Average	0.038	0.15	0.0046	–	–	0.0063	0.098	0.17
Health-care level II								
Antigua and Barbuda [B43]	–	–	–	–	–	–	–	0
Brazil	–	–	–	–	–	–	–	0.033
Dominica [B43]	–	–	–	–	–	–	–	0
Grenada [B43]	–	–	–	–	–	–	–	0
Jordan	0.021	0.047	–	–	–	–		0.13
Mexico	0.0064	0.031	0.00001	0	^{32}P, ^{153}Sm	0.0002	0.0002	0.038
Oman	0	0	0	0	0	0	0	0
Pakistan	0.0034	0.016	0.00004	0	^{131}I	0.0001	0	0.028
Peru	0.0085	0.0085	0	–	^{32}P, ^{153}Sm	0.017	–	0.034
Saint Kitts and Nevis [B43]	–	–	–	–	–	–	–	0
Saintt Lucia [B43]	–	–	–	–	–	–	–	0
St Vincent and the Grenadines [B43]	–	–	–	–	–	–	–	0
Tunisia	0.020	0.022	0	0	0	0	0	0.042
Turkey	0.031	0.014	0.0005	0.0023	0	0.0023	0	0.048
Average	0.011	0.020	0.0001	–	–	0.0017	0.0001	0.036

Table 67 (continued)

Country / area	*Thyroid malignancy* ^{131}I	*Hyper-thyroidism* ^{131}I	*Polycythaemia vera* ^{32}P	*Bone metastases*			*Synovitis* ^{90}Y	*Total number of all treatments*
				^{89}Sr	*Other*	*Total*		
Health-care level III								
Morocco	0.0045	0.030	0	0	0	0	0	0.035
Sudan	0.0008	0.0033	0	0	0.0023 (^{32}P)	0.0023	0	0.0064
Average	0.0027	0.017	0	–	–	0.0011	0	0.021
Health-care level IV								
Ethiopia	0	0.0004	0	0	0	0	0	0.0004
United Rep. of Tanzania	0	0.0002	0	0	0	0	0	0.0002
Average	0	0.0004	0	–	–	0	0	0.0004

a These revised data were received by the Committee after completion of the global analysis.

The entries in this Table are qualified as follows:

Argentina: On the basis of data from a sample of 25% of nuclear medicine centres.
Brazil: Survey data for Paraná State (with a population of 9 million and a social and economic profile above the average for Brazil).
Bulgaria: Data for 'Synovitis' relate to use of ^{198}Au.
Canada: On the basis of data for the province of Ontario (representing about 37% of population).
Cyprus: Survey data relating to 90% of population.
Finland: 'Bone metastases'treatments also conducted using ^{153}Sm (with a frequency of 0.0098 per 1,000 population) and ^{186}Re (with a frequency of 0.0004 per 1,000); total for synovitis also includes use of ^{166}Ho (with a frequency of 0.0002 per 1,000).
Germany: Total for 'Bone metastases' relates to use of ^{89}Sr and ^{186}Re; total for synovitis also includes use of ^{169}Er and ^{186}Re.
Mexico: No information on radionuclide for synovitis.
Netherlands: Total for 'Bone metastases' relates to use of ^{186}Re and ^{89}Sr.
Peru: Total for 'Bone metastases' relates to use of ^{153}Sm, ^{32}P and ^{89}Sr.
Turkey: On the basis of data from Hacettepe University Hospital.
Austria, Czech Republic, France, Greece, Hungary, Israel, Lithuania, Norway, Portugal, Switzerland: No information available on radionuclides used.

Table 68
Percentage contributions by treatment type to annual total numbers of therapeutic administrations of radiopharmaceuticals (1991-1996)
Based on data and qualifications from Table 67

Country / area	*Thyroid malignancy*	*Hyper-thyroidism*	*Polycythaemia vera*	*Bone metastases*	*Synovitis*	*Total of all treatments*
Health-care level I						
Argentina	38	62	0	0	0	100
Austria [H60]	6.3	61	0.2	2.6	0.9	100
Bulgaria	34	31	5.0	0	30	100
Canada	10	80	1.3	1.6	5.9	100
Croatia	45	55	0	0	0	100
Cyprus	60	25	0	15	0	100
Czech Republic	19	22	0.4	18	41	100
Denmark	6.8	93	0	0.3	0	100
Ecuador	31	64	0	4.9	0	100
Finland [K59]	20	64	12	2.5	1.9	100
France [H60]	-	-	-	7.1	-	100
Germany	22	70	0.6	1.3	4.5	100
Greece [H60]	30	52	-	11	7.1	100
Hungary	19	78	0.9	0	1.9	100
Ireland	6.7	85	5.6	2.3	-	100
Israel [H60]	1.3	-	-	0.3	0.3	100
Italy	51	45	1	0	0	100
Kuwait	29	68	0	3.1	0	100
Lithuania	23	77	0	0	0	100
Netherlands	11	72	3.9	5.1	7.7	100
New Zealand [L28]	20	64	7.3	5.3	2.9	100
Norway [H60]	14	78	0.3	6.2	0.4	100
Portugal [H60]	51	43	0.7	3.8	0.6	100
Qatar	0	100	0	0	0	100
Romania	74	26	0	0	0	100
Slovakia	68	30	0	0	0.8	100
Slovenia	0	92	0.3	2.4	4.7	100
Sweden	3.3	81	8.6	8.0	0.3	100
Switzerland [H60]	10	56	0.6	4.8	12	100
United Arab Emirates	55	45	0	0	0	100
United Kingdom [C27]	8.0	80	5.0	3.7	2.8	100
Average [a]	21	68	2.0	3.0	4.4	100
Health-care level II						
Jordan	16	35	-	-	-	100
Mexico	17	82	0.03	0.7	0.7	100
Pakistan	12	58	0.2	0.2	0	100
Peru	25	25	0	50	-	100
Tunisia	47	53	0	0	0	100
Turkey	65	29	1.0	4.8	0	100
Average [a]	29	54	0.3	5.0	0.2	100
Health-care level III						
Morocco	13	87	0	0	0	100
Sudan	13	51	0	36	0	100
Average [a]	13	81	0	5.5	0	100
Health-care level IV						
Ethiopia	0	100	0	0	0	100
United Rep. of Tanzania	14	86	0	0	0	100
Average [a]	3.1	97	0	0	0	100

a Overall averages for sample calculated as total number of each particular type of treatment divided by total number of all treatments.

Table 69
Distribution by age and sex of patients undergoing therapeutic treatments with radiopharmaceuticals (1991–1996)
Data from UNSCEAR Survey of Medical Radiation Usage and Exposures

Health-care level	*Country*	*Age distribution (%)*			*Sex distribution (%)*	
		0–15 years	*16–40 years*	*>40 years*	*Male*	*Female*
Thyroid malignancy						
I	Argentina	5	49	46	20	80
	Bulgaria	0	43	57	27	73
	Canada	0	43	57	20	80
	Croatia	0	14	86	12	88
	Czech Republic	4	29	67	29	71
	Ecuador	4	50	46	29	71
	Finland	0	–	–	–	–
	Ireland	0	30	70	25	75
	Japan	0	9	91	23	77
	Kuwait	3	64	33	27	73
	Panama	0	38	62	20	80
	Romania	4	30	66	34	66
	Slovakia	0	40	60	–	–
	United Arab Emirates	0	41	59	57	43
	Average	3	37	60	24	76
II	Jordan	2	43	55	12	88
	Mexico	2	46	52	20	80
	Pakistan	11	56	33	48	52
	Peru	0	30	70	30	70
	Turkey	0	51	49	40	60
	Average	2	49	49	36	64
III	Morocco	0	100	0	–	–
	Sudan	0	60	40	65	35
	Average	0	94	6	65	35
IV	United Rep. of Tanzania	0	0	100	0	100
Hyperthyroidism						
I	Argentina	2	46	52	19	81
	Bulgaria	0	81	19	3	97
	Canada	4	39	57	27	73
	Croatia	0	13	87	14	86
	Czech Republic	0	9	91	9	91
	Ecuador	9	58	33	19	81
	Finland	0	–	–	–	–
	Japan	0	23	77	18	82
	Jordan	3	43	54	32	68
	Kuwait	0	60	40	40	60
	Romania	0	35	65	20	80
	Slovakia	0	35	65	–	–
	United Arab Emirates	8	23	69	35	65
	Average	3	37	60	22	78
II	Jordan	3	43	54	32	68
	Mexico	2	49	49	16	84
	Pakistan	14	54	32	39	61
	Peru	0	70	30	20	80
	Average	7	51	42	26	74
III	Morocco	0	100	0	–	–
	Sudan	0	75	25	6	94
	Average	0	98	2	6	94
IV	Ethiopia	0	0	100	8	92
	United Rep. of Tanzania	0	100	0	15	85
	Average	0	19	81	9	91

Table 69 (continued)

Health-care level	*Country*	*Age distribution (%)*			*Sex distribution (%)*	
		0–15 years	*16–40 years*	*>40 years*	*Male*	*Female*
Polycythaemia vera						
I	Bulgaria	0	0	100	90	10
	Canada	0	0	100	68	32
	Finland	0	–	–	–	–
	Ireland	0	0	100	50	50
	Average	0	0	100	67	33
II	Mexico	0	0	100	100	0
	Pakistan	0	17	83	100	0
	Average	0	15	85	100	0
Bone metastases						
I	Canada	0	0	100	67	33
	Czech Republic	0	0	100	77	23
	Ecuador	0	10	90	65	35
	Kuwait	–	–	–	100	0
	Average	0	0	100	75	25
II	Mexico	0	0	100	70	30
	Pakistan	33	33	34	100	0
	Peru	0	0	100	50	50
	Turkey	0	1	99	51	49
	Average	0	1	99	52	48
III	Sudan	0	30	70	50	50
Synovitis						
I	Bulgaria	0	47	53	63	37
	Canada	0	0	100	50	50
	Czech Republic	36	37	27	73	27
	Slovakia	0	0	100	–	–
	Average	23	26	51	66	34
II	Mexico	0	87	13	83	17
All therapeutic procedures						
I	Argentina	3	47	50	19	81
	Bulgaria	0	54	46	34	66
	Croatia	0	13	87	16	84
	Czech Republic	4	9	87	53	47
	Ecuador	7	53	40	24	76
	Kuwait	1	61	38	38	64
	Slovakia	0	38	62	–	–
	United Arab Emirates	3	33	64	47	53
	Average	3	38	59	28	72
II	Jordan	2	53	45	29	71
	Mexico	2	48	50	17	83
	Pakistan	16	37	47	72	28
	Average	9	43	48	45	55
IV	Ethiopia	0	0	100	8	92
	United Rep. of Tanzania	0	85	15	13	87
	Average	0	19	81	9	91

The entries in this Table are qualified as follows:

Argentina: On the basis of data from a sample of 25% of nuclear medicine centres.
Canada: Data from London Health Sciences Centre, SW Ontario (representing 50% of the services provided to population of about 1 million).
Turkey: Survey data from Gülhane Military Hospital, Hacettepe University Hospital and Samsun Ondokuz Mayis University Hospital.

Table 70
Average [a] activities administered (MBq) in therapeutic treatments with radiopharmaceuticals (1991-1996)
Data from UNSCEAR Survey of Medical Radiation Usage and Exposures unless otherwise indicated

Country / area	Thyroid malignancy	Hyperthyroidism	Polycythaemia vera	Bone metastases			Synovitis	
	^{131}I iodide	^{131}I iodide	^{32}P phosphate	^{89}Sr chloride	^{32}P phosphate	Other	^{90}Y	Other
Health-care level I								
Argentina	4 477 (±1258)	433 (±122)	–	–	–	–	–	–
Bulgaria	3 300 (3 000–5 500)	185	(74–370)	–	–	–	–	–
Canada	(5 500–7 400)	(300–1 500)	185	–	–	–	300	–
Croatia	4 706 (3 452–5 960)	726 (±510)	–	–	–	–	–	–
Denmark	–	420	–	–	–	–	–	–
Ecuador	3 700 (± 50%)	370 (±50%)	–	150	5	–	–	–
Finland [K59]	4 334 (3 500–5 550)	321 (148–425)	154 (110–222)	148	–	1 300 [d], 2 564 (1 295–3 000) [f]	168 (148–185)	555 [b]
Germany	(1 000–8 000)	(200–2 000)	(150–200)	150	–	1 300 [d]	168	(15–30) [c], (35–185) [d]
Ireland	3 700 (1 110–7 400)	400 (185–500)	148 (111–185)	150	–	–	–	–
Italy	5550 (2 500–11 100)	555 (185–1 110)	185	–	–	–	–	–
Japan	3 330	160	–	–	–	–	–	–
Kuwait	7 400	106	–	148	–	–	–	–
Netherlands	5 500 (8 000 max.)	500 (1800 max.)	(250–400)	150	–	1 300 [d]	185	–
New Zealand [L28]	3 303 (1 000–7 000)	381 (150–1 000)	174 (120–259)	150	–	–	185	–
Panama	5 550 (2 934–8 166)	463 (±131)	–	–	–	–	–	–
Slovakia	3 700 (2 600–5 550)	260 (185–370)	–	–	–	–	–	–
Slovenia	–	350 (185–550)	37	150	–	–	185	–
Sweden	6 800 (4 000–7 400)	525 (240–1 500)	200 (160–400)	150 (125–150)	–	–	170 (110–220)	–
United Arab Emirates	3 700 (2 275–5 550)	422 (200–462)	–	–	–	–	–	–
United Kingdom [C27]	–	–	166	136	–	–	200	–
Average	4 760	415	170	140	–	–	250	–
Health-care level II								
Jordan	3 700 (±20%)	550 (±20%)	–	–	–	–	–	–
Mexico	3 700 (1 840–5 560)	370 (185–555)	148 [e] (111–185)	–	185	46 [f] (37–555)	–	–
Peru	5 550 (5 000–6 000)	260 (200–300)	–	148	444	3 885 (3 500–4 000) [f]	–	–
Turkey	3 238	185	148	111	–	–	–	–
Average	3 510	340	148	111	–	–	–	–

Table 70 (continued)

Country / area	*Thyroid malignancy*	*Hyperthyroidism*	*Polycythaemia vera*	*Bone metastases*			*Synovitis*	
	^{131}I iodide	*^{131}I iodide*	*^{32}P phosphate*	*^{89}Sr chloride*	*^{32}P phosphate*	*Other*	*^{90}Y*	*Other*
Health-care level III								
Morocco	3 700 (3 330–4 440)	296 (222–444)	–	–	–	–	–	–
Sudan	3 710	300	–	–	291	–	–	–
Average	3 700	300	–	–	–	–	–	–
Health-care level IV								
Ethiopia	–	185 (111–370)	–	–	–	–	–	–
United Rep. of Tanzania	3 500	350 (±2%)	–	–	–	–	–	–
Average	3 500	220	–	–	–	–	–	–

a Range or standard deviation in parentheses.
b Data relate to use of ^{166}Ho.
c Data relate to use of ^{169}Er.
d Data relate to use of ^{186}Re.
e Data relate to use of ^{90}Y.
f Data relate to use of ^{153}Sm.

The entries in this Table are qualified as follows:

Argentina: On the basis of data from a sample of 25% of nuclear medicine centres.
Canada: Data from London Health Sciences Centre, SW Ontario (representing 50% of the services provided to population of about 1 million).
Turkey: Survey data from Gülhane Military Hospital, Hacettepe University Hospital, and Samsun Ondokuz Mayis University Hospital.

Table 71
Annual numbers [a] of radiopharmaceutical treatments per 1,000 population assumed in global model for radionuclide therapy practice (1991-1996)

Disease	*Level I*	*Level II*	*Level III*	*Level IV*	*World*	*% Contribution to world total*
Thyroid malignancy	0.035	0.010	0.003	0.00001	0.015	23
Hyperthyroidism	0.11	0.019	0.017	0.00035	0.042	65
Polycythaemia vera	0.003	0.0001	0	0	0.001	1
Bone metastases	0.005	0.002	0.001	0	0.002	4
Synovitis	0.007	0.0001	0	0	0.002	3
Total	0.17	0.036	0.021	0.0004	0.065	100

a Estimated on the basis of average percentage distributions by treatment type (Table 68) and average total frequencies (Tables 67) observed for each health-care level.

Table 72
Temporal trends in annual frequency of radiopharmaceutical treatments per 1,000 population
Data from UNSCEAR Surveys of Medical Radiation Usage and Exposures

Country	*1970–1979*	*1980–1984*	*1985–1990*	*1991–1996*
Health-care level I				
Argentina	–	–	0.16	0.19
Australia	0.15	0.15	0.14	–
Austria	–	–	–	0.29
Belgium	4	–	0.31	–
Bulgaria	–	–	–	0.03
Canada	–	–	0.88	0.30
Cayman Islands	–	–	–	0
Croatia	–	–	–	0.031
Cyprus	–	–	–	0.080
Czechoslovakia [a]	0.073	0.12	0.18	–
Czech Republic	–	–	–	0.25
Denmark	0.13	0.18	0.21	0.46
Ecuador [b]	(0.007)	–	(0.0065)	0.035
Finland	0.32	0.36	–	0.44
France	–	–	–	0.13
Germany	–	–	–	0.39
Greece	–	–	–	0.16
Hungary	–	–	–	0.11
Ireland	–	–	–	0.12
Israel	–	–	–	0.060
Italy	–	–	–	0.11
Japan	0.049	0.025	0.030	–
Kuwait	–	–	0.018	0.13
Lithuania	–	–	–	0.29
Luxembourg	–	–	0.19	–
Malta	–	–	0.075	–
Netherlands	–	–	–	0.29 [d]
New Zealand	0.16	0.18	0.17	0.16
Norway	0.059	–	0.12	0.26
Portugal	–	–	–	0.068
Qatar	–	–	–	0.044
Romania	–	0.051	0.052	0.068
Russian Federation [c]	(0.02)	(0.02)	(0.00)	0.010
Slovakia	–	–	–	0.11
Slovenia	–	–	–	0.30
Spain	–	–	–	0.20
Sweden	0.34	–	0.43	0.4
Switzerland	1.55	–	–	0.27
United Arab Emirates	–	–	–	0.024
United Kingdom	–	0.20	–	0.25
Yugoslavia [a]	–	–	0.11	–
Average	0.086	0.093	0.10	0.17

Table 72 (continued)

Country	*1970–1979*	*1980–1984*	*1985–1990*	*1991–1996*
Health-care level II				
Antigua and Barbuda	–	–	–	0
Barbados	–	–	0.15	–
Brazil	–	–	–	0.033
China	–	–	0.035	–
Dominica	–	–	–	0
Grenada	–	–	–	0
India	–	–	0.0036	–
Iraq	–	–	0.013	–
Jordan	–	–	–	0.13
Mexico	–	–	–	0.038
Oman	–	–	–	0
Pakistan	–	–	–	0.028
Peru	–	–	0.011	0.034
Saint Kitts and Nevis	–	–	–	0
Saint Lucia	–	–	–	0
Saint Vincent and the Grenadines	–	–	–	0
Tunisia [e]	(0.35)	–	(0.042)	0.042
Turkey	–	–	0.008	0.048
Average	0.044	–	0.021	0.036
Health-care level III				
Egypt	0.064	0.061	0.062	–
Jamaica [b]	(0.17)	–	(0.005)	–
Morocco	–	–	–	0.035
Myanmar	0.014	0.011	0.005	–
Sudan	0.001	0.003	0.006	0.0064
Thailand	0.008	0.011	0.013	–
Average	0.025	0.025	0.025	0.021
Health-care level IV				
Ethiopia	–	–	–	0.0004
United Rep. of Tanzania	–	–	–	0.0002
Average	–	–	–	0.0004

a Historical data.
b Categorized in health-care level II in previous analyses.
c Historical data were not included in previous analyses.
d These revised data were received by the Committee after completion of the global analysis.
e Categorized in health-care level III in previous analyses.

Table 73
Temporal trends in the average annual number [a] of the various types of radionuclide therapy treatments per 1,000 population
Data from UNSCEAR Surveys of Medical Radiation Usage and Exposures

Disease/site	*Period*	*Average annual number of treatments per 1,000 population*			
		Health-care level I	*Health-care level II*	*Health-care level III*	*Health-care level IV*
Thyroid malignancy	1970–1979	0.059	0.023	0.010	–
	1980–1984	0.033	–	0.009	–
	1985–1990	0.063	0.0004	0.011	–
	1991–1996	0.038	0.011	0.003	0
Hyperthyroidism	1970–1979	0.088	–	0.023	–
	1980–1984	0.10	–	0.024	–
	1985–1990	0.022	0.0004	0.020	–
	1991–1996	0.15	0.020	0.017	0.0004
Polycythaemia vera	1970–1979	0.014	–	–	–
	1980–1984	0.024	–	0.001	–
	1985–1990	0.016	0.0001	0.002	–
	1991–1996	0.005	0.0001	0	0
Total of all radionuclide therapy	1970–1979	0.086	0.044	0.025	–
	1980–1984	0.093	–	0.025	–
	1985–1990	0.10	0.021	0.025	–
	1991–1996	0.17	0.036	0.021	0.0004

a Overall averages calculated from national data as the total number of treatments divided by the total population for each treatment category. Data for 1991–1996 from Table 67; since the total population is not the same for each treatment category due to the lack of comprehensive national data for all countries included in the analysis, these average numbers can not be expected to be additive.

Table 74
Estimated annual numbers of therapeutic treatments with radiopharmaceuticals in the world 1991–1996

Health-care level	*Population (millions)*	*Annual number of treatments*	
		Millions	*Per 1,000 population*
I	1 530	0.3	0.2
II	3 070	0.1	0.04
III	640	0.01	0.02
IV	565	0.0002	0.0004
World	5 800	0.4	0.065

Table 75
Distributions of effective doses to volunteers from administrations of radiopharmaceuticals during participation in research studies in Germany
[B78]

Year	*No of research studies*		*Range of effective dose (mSv)*	*Fraction of population by volunteer category (%)*		
	PET	*Other*		*Healthy persons*	*Patients*	*All*
1997	17 [a]	19 [b]	≤ 1	50.5	0	3.6
			> 1 – 6	16.7	8.1	8.7
			>6 – 10	3.0	17.9	16.8
			>10 – 20	23.8	68.3	65.1
			>20 – 50	6.0	5.0	5.1
			>50	0	0.7	0.7
1998	28 [c]	15 [d]	≤ 1	11.6	6.8	7.2
			> 1 – 6	41.3	30.4	31.4
			>6 – 10	0	4.1	3.8
			>10 – 20	41.3	44.2	44.0
			>20 – 50	5.8	14.1	13.3
			>50	0	0.4	0.3

a Distribution by radionuclide: 13 ^{18}F, 2 ^{15}O, 2 ^{11}C, and 1 ^{68}Ga. Distribution by speciality: 4 neurology/psychiatry, 12 oncology and 1 cardiology.
b Distribution by radionuclide: 8 ^{99m}Tc, 7 ^{123}I, 2 ^{131}I, and 1 ^{81m}Kr. Distribution: 6 neurology/psychiatry, 9 oncology, 1 cardiology and 3 other.
c Distribution by radionuclide: 14 ^{18}F, 6 ^{15}O, 8 ^{11}C, and 1 ^{13}N. Distribution: 18 neurology/psychiatry, 6 oncology , 3 cardiology and 2 other.
d Distribution by radionuclide: 13 ^{99m}Tc, 1 ^{123}I, 1 ^{201}Tl, and 1 ^{81m}Kr. Distribution: 4 neurology/psychiatry, 5 oncology, 2 cardiology and 4 other.

Table 76
Guidelines for notification of incidents in the United Kingdom involving radiation equipment used for medical exposure
[H62]

Type of diagnostic examination	*Guideline multiplying factor* [a]
Barium enemas, barium meals, IVUs, angiography and other such procedures involving fluoroscopy (including digital radiology) and CT	3
Nuclear medicine: intended effective dose > 5mSv	3
Lumbar spine, abdomen, pelvis, mammography and all other examinations not otherwise included	10
Nuclear medicine: intended effective dose in the range 0.5–5 mSv	10
Extremities, skull, chest, dental examinations and other simple examinations such as elbow, knee and shoulder	20
Nuclear medicine: intended effective dose < 0.5 mSv	20
Type of treatment	*Guideline multiplying factor* [a]
Beam therapy, brachytherapy	1.1 (whole course) 1.2 (any fraction)
Radionuclide therapy	1.2 (any administration)

a For application to the ratio of suspected dose to intended dose, when deciding whether the patient exposure from an incident was ‘much greater than intended’.

Table 77
Estimated annual global practice and doses to the world population [a] from medical uses of radiation [b] (1991–1996)

Medical radiation use	*Number of procedures (millions)*					*Effective dose per caput (mSv)*					*Collective effective dose (10^3 man Sv)*				
	Level I	*Level II*	*Level III*	*Level IV*	*World*	*Level I*	*Level II*	*Level III*	*Level IV*	*World*	*Level I*	*Level II*	*Level III*	*Level IV*	*World*
Diagnosis															
Medical x-ray examinations	1 410	470	13	11	1 910	1.2	0.14	0.02	0.02	0.4	1 900	425	14	13	2 300
Dental x-ray examinations	475	42	0.1	0.1	520	0.01	0.001	<0.0001	<0.0001	0.002	9	4	0.01	0.01	14
Nuclear medicine procedures	29	3	0.2	0.01	32	0.08	0.008	0.006	0.0003	0.03	120	23	4	0.2	150
Total	1 900	520	13	11	2 500	1.3	0.15	0.03	0.02	0.4	2 000	450	18	13	2 500
Therapy [c]															
Radiotherapy treatments	2.6	2.2	0.3	0.04	5.1										
Nuclear medicine treatments	0.3	0.1	0.01	0.0002	0.4										
Total	2.9	2.3	0.3	0.04	5.5										

a World population estimated to be 5,800 million in 1996 with following distribution between health-care levels of global model: 1,530 million (26%) in level I; 3,070 million (53%) in level II; 640 million (11%) in level III; and 565 million (10%) in level IV.

b Since, as discussed in Section I.C, many of these exposures are received by patients nearing the end of their lives and the doses are not distributed evenly amongst the population, these doses should not be used for the assessment of detriment.

c Complete courses of treatment.

Table 78
Trends in annual global use of radiation for diagnosis

UNSCEAR Report	*Annual use of medical x rays*				*Annual use of dental x rays*				*Annual use of radiopharmaceuticals*				*Annual per caput dose from global practice* [a] *(mSv)*
	Number of exams (millions)	*Frequency per 1,000 population*	*Collective dose (10^3 man Sv)*	*Per caput dose (mSv)*	*Number of exams (millions)*	*Frequency per 1,000 population*	*Collective dose (10^3 man Sv)*	*Per caput dose (mSv)*	*Number of exams (millions)*	*Frequency per 1,000 population*	*Collective dose (10^3 man Sv)*	*Per caput dose (mSv)*	
1958 [U13]	–	[c]	–	–	–	[i]	–	–	–	–	–	–	[o]
1962 [U12]	–	[d]	–	–	–	[j]	–	–	–	[k]	–	–	[p]
1972 [U8]	[b]	[e]	–	–	–	–	–	–	–	[l]	–	–	[q]
1977 [U7]	–	[f]	–	–	–	–	–	–	–	–	–	–	[r]
1982 [U6]	–	300–900[g]	–	1[h]	–	–	–	–	–	10–40[m]	–	[n]	0.4
1988 [U4]	1 380	280	1 800	0.35	340	70	17	0.003	23.5	4.7	74	0.015	0.4
1993 [U3]	1 600	300	1 600	0.3	–	–	18	0.003	24	4.5	160	0.03	0.3
2000 [Present]	1 910	330	2 300	0.4	520	90	14	0.002	32.5	5.6	150	0.03	0.4

a Includes diagnostic uses of x rays and radiopharmaceuticals.
b Annual increases by a few percent noted for technically developed countries.
c Range of 380–1,270 per 1,000 in survey data from 9 developed countries.
d Range of 260–410 per 1,000 in survey data from 12 countries.
e Range of 39–1,240 per 1,000 in survey data from 12 countries.
f Range of 35–1,660 per 1,000 in survey data from 11 countries.
g Survey data (excluding mass surveys) for industrialized countries; 100–200 per 1,000 in developing countries.
h Estimate for industrialized countries; lower value for developing countries where examinations are less frequent.
i Range of 21–400 per 1,000 in survey data from 4 developed countries.
j Range of 10–400 per 1,000 in survey data from 10 developed countries.
k Range of 0.1–1.7 per 1,000 in survey data from 8 countries.
l Range of 1.7–10.1 per 1,000 in survey data from 7 countries.
m Range for industrialized countries; 0.2–2 per 1,000 in developing countries.
n Range of 0.02–0.15 mSv for industrialized countries.
o GSD same order as from natural sources (estimated range 0.2–2 mGy per year). Per capita mean marrow dose similar to that from natural sources (2.3 mGy per year).
p Relative to risk from natural radiation: 0.3 for hereditary effects and 0.4–0.8 for risk of leukaemia.
q Limited survey data (relative to annual doses from natural sources): GSD in range 0.1 – 0.5, per caput marrow dose in range 0.3 – 2.
r 0.5–1 mSv in countries with developed radiological facilities; 0.01 mSv in countries with limited facilities. Globally, 0.2 relative to dose from natural sources.

Table 79
Trends in annual global use of radiation for therapy

UNSCEAR Reports	*Teletherapy and brachytherapy*		*Radiopharmaceuticals*	
	Annual number of treatments [a] (millions)	*Annual frequency per 1,000 population*	*Annual number of treatments (millions)*	*Annual frequency per 1,000 population*
1988 [U4]	4.3	0.9	0.7	0.14
1993 [U3]	4.9	0.9	0.2	0.04
2000 [Present]	5.1	0.9	0.4	0.065

a Complete courses of treatment.

References

PART A

Responses to UNSCEAR Survey of Medical Radiation Usage and Exposures

Country	*Respondent*
Argentina	A. Curti. Nuclear Regulatory Authority, Buenos Aires
Australia	D. Webb. Australian Radiation Laboratory, Yallambie
Bahrain	Response submitted by the Permanent Mission of the State of Bahrain to the United Nations in Geneva
Belarus	G. Chijz. Ministry of Health, Minsk
Belgium	J. Van Dam. Katholieke Universtitet Leuven
Brazil	J. Tilly. Federal Centre of Technological Education of Paraná, Curitiba
Bulgaria	G. Vasilev. National Centre of Radiobiology and Radiation Protection, Sofia
Canada	S. Vlahovich. Radiation Protection Bureau, Ottawa
Cayman Islands	R Namburi. Cayman Islands Government Hospital, Grand Cayman Island
China	D. Li. China Atomic Energy Authority, Beijing
China (Taiwan Province)	C.-N. Guan. Atomic Energy Council, Taipei
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Kuwait	J. Al-Mudaires. Ministry of Health, Dahayat Abdulla Al-Salem
Lebanon	N. Khoury and M. Nasreddine. Lebanese Atomic Energy Commission, Beirut
Libyan Arab Jamahiriya	D. Abouhadra. Scientific Research, IAEA Division, Tripoli
Lithuania	B. Švykaitė. Radiation Protection Centre, Vilnius

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Netherlands	L.W. Meinders. Inspectorate for Health Care, Rijswijk
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Philippines	B. San Juan. Radiation Health Service, Department of Health, Manila
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18 May 2016

Sources and Effects of Ionizing Radiation: United Nations Scientific Committee on the Effects of Atomic Radiation 2000 Report

Volume I

Annex E (Occupational radiation exposures)

Corrigendum

1. Page 647, table 43, last row of the section headed "Total of all uses"

For 14 000 *read* 14 400

For 0.1 *read* 1.31

V.16-02702 (E)

ANNEX E

Occupational radiation exposures

CONTENTS

INTRODUCTION

1. There is a wide variety of situations in which people at work are exposed to ionizing radiation. These situations range from handling small amounts of radioactive material, such as for tracer studies, to operating radiation-generating or -gauging equipment, to working in installations of the nuclear fuel cycle. There are also situations where the exposure of workers to natural sources of radiation is sufficiently high to warrant its management and control as an occupational hazard.

2. The conventional definition of occupational exposure to any hazardous agent includes all exposures incurred at work, regardless of source [I18]. However, to distinguish the exposures that should be subject to control by the operating management from the exposures arising from the general radiation environment in which all must live, the term "occupational radiation exposure" is usually taken to mean those exposures that are received at work that can reasonably be regarded as the responsibility of the operating management [I5, I12]. Such exposures are normally also subject to regulatory control, with the requirements for practices as defined by ICRP in its Publication 60 [I12] being applied. The exposures are usually determined by individual monitoring, but sometimes by other methods. An important objective of such determinations is to provide information on the adequacy of protection measures, and they are a key input to operational decisions related to the optimization principle. In addition, they demonstrate compliance with relevant dose limits.

3. The Committee is interested in reviewing the distributions of individual annual effective doses and annual collective effective doses from occupational radiation exposures in various sectors of industry or from various types of source. It is of particular interest to examine the changes that have taken place over time with the introduction of improved practices, new technology, or revised regulations.

4. Data on occupational radiation exposures were given in the UNSCEAR 1977, 1982, 1988, and 1993 Reports [U3, U4, U6, U7]. Differences existed, and indeed still do exist, among countries in the procedures for monitoring and reporting occupational exposures; these differences reflect, among other things, differences in regulatory requirements. As a result, comparisons of data on doses are not always straightforward and may be somewhat limited in scope. Over the years, such comparisons have shed light on these differences, and a number of recommendations have been made. Particular attention was drawn to the need for data on the pattern of dose accumulation over a working lifetime, especially for those occupations in which higher levels of individual exposure are encountered, and to the value of reporting doses in narrower bands of individual dose. Such data are not readily available, however.

5. The main objectives of the analysis of occupational radiation exposures remain, as in the previous assessments of the Committee, as follows:

(a) to assess annual external and committed internal doses and cumulative doses to workers (both the average dose and the distribution of doses within the workforce) for each major practice involving the use of ionizing radiation. This provides a basis for estimating the average individual risks in a workforce and within its subgroups;
(b) to assess the annual collective doses to workers for each of the major practices involving the use of ionizing radiation. This provides a measure of the contribution made by occupational exposures to the overall impact of that use and the impact per unit practice;
(c) to analyse temporal trends in occupational exposures in order to evaluate the effects of changes in regulatory standards or requirements (e.g. changes in dose limits and increased attention to making doses as low as reasonably achievable), new technological developments, modified work practices, and, more generally, radiation protection programmes;
(d) to compare exposures of workers in different countries and to estimate the worldwide levels of exposure for each significant use of ionizing radiation; and
(e) to evaluate data on accidents involving the exposure of workers to levels of radiation that have caused clinical effects.

6. The Committee has evaluated five-year average exposures beginning in 1975. The detailed data presented in this Annex are for 1990–1994, but data for previous periods are provided for comparison. Occupational exposures in each major practice or work activity are reported, indicating trends with respect to the data in the earlier assessments and identifying the main contributors. Exposures from different countries are compared, and worldwide exposures are determined for each category of work in which radiation exposures occur.

7. The data in this Annex were obtained in much the same way as the data for the UNSCEAR 1993 Report [U3]. Data on occupational exposures from man-made sources of radiation (nuclear power, defence activities, and industrial and medical uses of radiation) are systematically collected by many national authorities. The Committee obtained these data by means of a questionnaire, the UNSCEAR Survey of Occupational Radiation Exposures, which it distributed to countries throughout the world. The data have been supplemented by other (usually published) sources of information; for the nuclear power industry, for example, the source is the databank of the Organization for Economic Cooperation and Development/Nuclear Energy Agency (OECD/NEA) [O2, O5]. However, the data set is by no means complete, and procedures have been developed by the Committee to derive worldwide doses from the data available for particular occupational categories (see Section I.E).

8. The data on doses arising in the commercial nuclear fuel cycle are reasonably complete. Where data are missing or incomplete, doses can be calculated from worldwide statistics on capacity and production in the various stages of the fuel cycle. Thus the worldwide annual collective effective dose from a given part of the nuclear fuel cycle is estimated to be the total of the annual collective effective doses from the reported data scaled according to the total worldwide statistic (uranium mined, fuel fabricated, energy generated, etc.).

9. For exposures to radiation in other operations, the calculations are scaled according to the gross domestic product (GDP) of countries. The GDP is reasonably correlated with the level of both industrial activity and medical care in a country. To make the calculations more reliable, the values of GDP are applied to regional data, and the results are summed over all regions. For this purpose, the world was divided into seven regions: the OECD excluding the United States; the United States; eastern Europe and the countries of the former USSR; Latin America; the Indian subcontinent; east and south-west Asia; and the remaining countries.

10. Exposures from natural sources of radiation, with a few exceptions, have generally not been subject to the same degree of control as exposures from man-made sources. The few exceptions are exposures in uranium mines and mills and in practices where purified forms of naturally occurring radioactive substances, such as ^{226}Ra and thorium, are handled.

11. The principal natural sources of radiation exposure of interest other than those that have traditionally been directly related to the work (e.g. those in the mining and milling of uranium ores) are radon in buildings, non-uranium mines and other underground workplaces; cosmic rays at aircraft altitudes; and materials other than uranium or thorium ores that contain significant traces of natural radionuclides. The exposures of individuals in the first two situations are often comparable to, if not in excess of, the exposures currently received from man-made sources. Furthermore, there is some scope for the reduction of these exposures, particularly those from radon. The large number of workers involved, particularly in the mining industry, results in annual collective effective doses that are substantially higher than those from man-made sources of radiation.

I. DOSE MONITORING AND RECORDING PRACTICES

12. A number of difficulties are encountered in determining occupational exposures. External radiation fields may be non-uniform in space and time and may be of various types and a wide range of energies. Internal exposures may also occur. Workers may be frequently exposed, seldom exposed, or hardly exposed at all. The difficulties may be addressed in various ways, as reflected in the variety of monitoring procedures and dose recording practices adopted in countries throughout the world. This topic was addressed in some detail in the UNSCEAR 1993 Report [U3]. However, to the extent that attention still needs to be drawn to it or that changes have occurred that may affect the interpretation of results, the topic is discussed further in this Chapter.

A. QUANTITIES MEASURED

1. Protection quantities

13. The basic physical quantity used in radiological protection is the absorbed dose, D_T, averaged over an organ or defined tissue. The absorbed dose is expressed in the unit gray (Gy), with 1 Gy equal to 1 joule per kilogramme. To account for the type of the radiation and the differences in ionization density, a further quantity has been introduced, the equivalent dose, H_T, which is the average absorbed dose in an organ or tissue multiplied by a dimensionless factor called the radiation weighting factor, w_R. Equivalent dose is expressed in the unit sievert (Sv).

14. The effective dose, E, also expressed in Sv, has been defined to take account of the fact that the probability of stochastic effects for a given equivalent dose varies with the organ or tissue irradiated. The factor by which the equivalent dose in a tissue or organ is weighted is called the tissue weighting factor, w_T, the values being chosen such that the effective dose gives a measure of the radiation detriment irrespective of how that dose was received. In particular, this approach allows effective doses from external and internal exposures to be aggregated.

15. Effective dose and equivalent dose are the basic quantities for radiological protection purposes in which, for example, dose limits are expressed [I12]. The effective dose limit is intended to limit the total health detriment from radiation exposure due to stochastic effects. Limits on equivalent dose are required for skin and the lens of the eye to ensure that deterministic effects are avoided in these tissues. These protection quantities relate, as appropriate, to the sum of the effective or equivalent doses from external sources and the committed effective or equivalent doses from the intake of radionuclides. Dose quantities are discussed in detail in Annex A, "*Dose assessment methodologies*".

2. Quantities for external radiation exposure

16. The basic quantities for physical measurement include particle fluence, kerma, and absorbed dose. They are the quantities used by national standards laboratories.

However, the need for measurable quantities for external radiation exposure that can be related to the protection quantities has led to the development of operational quantities, which provide an estimate of effective or equivalent dose that avoids underestimation and excessive overestimation in most radiation fields encountered in practice.

17. There are three operational quantities of particular interest in the measurement of radiation fields for protection purposes: the ambient dose equivalent, $H^*(d)$; the directional dose equivalent, $H'(d, \Omega)$; and the personal dose equivalent, $H_p(d)$. All these quantities are based on the dose equivalent at a point and not on the concept of equivalent dose. The ambient dose equivalent and the directional dose equivalent are appropriate for environmental and area monitoring, the former for strongly penetrating radiation and the latter for weakly penetrating radiation. The ambient dose equivalent at a point in a radiation field is the dose equivalent that would be produced by the corresponding aligned and expanded field in the ICRU sphere at a depth d on the radius opposing the direction of the aligned field. The directional dose equivalent at a point is the dose equivalent that would be produced by the corresponding expanded field in the ICRU sphere at a depth d on a radius in a specified direction. The concepts of "expanded" and "aligned" fields are given in ICRU Report 39 [I19] to characterize fields that are derived from the actual radiation fields. In the expanded field, the fluence and its angular and energy distribution have the same values throughout the volume of interest as at the actual field at the point of reference. In the aligned and expanded field, the fluence and its energy distribution are the same as in the expanded field, but the fluence is unidirectional.

18. The personal dose equivalent, $H_p(d)$, is the dose equivalent in soft tissue below a specified point on the body at an appropriate depth d. This quantity can be used for measurements of superficial and deep organ doses, depending on the chosen value of the depth in tissue. The depth d is expressed in millimetres, and ICRU recommends that any statement of personal dose equivalent should specify this depth. For superficial organs, depths of 0.07 mm for skin and 3 mm for the lens of the eye are employed, and the personal dose equivalents for those depths are denoted by $H_p(0.07)$ and $H_p(3)$, respectively. For deep organs and the control of effective dose, a depth of 10 mm is frequently used, with the notation $H_p(10)$.

19. Personal dose equivalent quantities are defined in the body and are therefore not directly measurable. They vary from person to person and from location to location on a person, because of scattering and attenuation. However, $H_p(d)$ can be assessed indirectly with a thin, tissue-equivalent detector that is worn at the surface of the body and covered with an appropriate thickness of tissue equivalent material. ICRU recommends that dosimeters be calibrated under simplified conditions on an appropriate phantom [I20].

20. The relationship between the physical, protection, and operational quantities is illustrated in Figure I. They are discussed more fully in ICRP Publication 74 [I16], which provides conversion coefficients for use in radiological protection against external radiations. It was concluded that there is an acceptable agreement between the operational and protection quantities for radiation fields of practical significance when the operational quantities are based on the Q/LET relationship given in ICRP Publication 60 [I12].

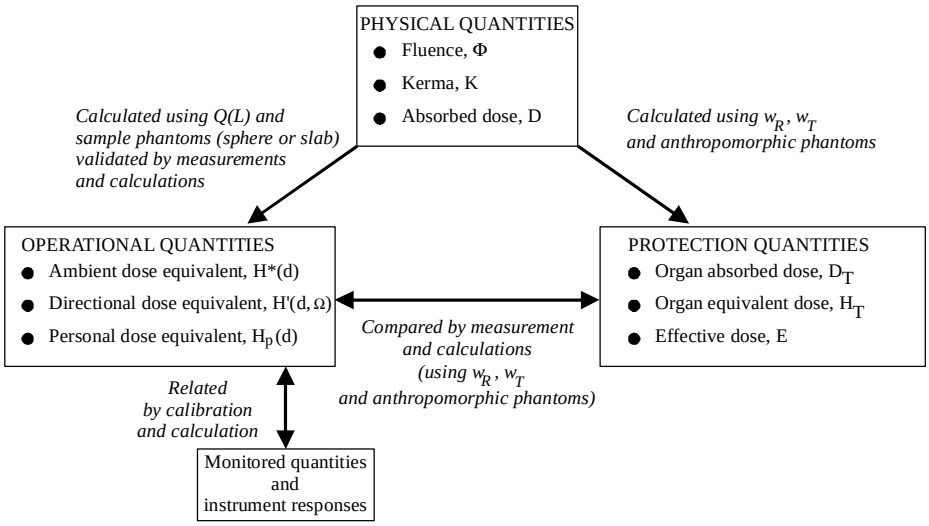

Figure I. Relationship of quantities for radiological protection monitoring purposes [I16].

21. In most practical situations, dosimeters provide reasonable approximations to the personal dose equivalent, $H_p(d)$, at least at the location of the dosimeter. When the exposure of the body is relatively low and uniform, it is common practice to enter the dosimeter reading, suitably calibrated, directly into the dose records as a surrogate for effective dose. However, because the personal dose equivalent generally overestimates the effective dose, this

practice results in overestimated recorded and reported doses, with the degree of overestimation depending on the energy of the radiation and the nature of the radiation field. For many practical situations involving relatively uniform exposure to fairly high-energy gamma radiation, the degree of overestimation is modest; for exposure to low-energy gamma or x radiation, the overestimation can be substantial. For photon energies below ~50 keV, the effective dose can be overestimated by a factor of 2, depending on the orientation of the body.

22. For exposure to spatially variable radiation fields or where there is partial shielding of the body or extreme variations in the distances of parts of the body from the source, the relationships between the dosimeter measurement and the effective dose are more variable and complex. Where the circumstances so justify, additional measurements or theoretical analysis have been used to establish reliable relationships on a case-by-case basis for the exposure conditions of interest. The direct entry of dosimeter measurements into dose records in these more complex situations (or the use of very simple and deliberately cautious assumptions to establish the relationships between the two quantities) leads, in general, to overestimates in the recorded exposures. Where such practice has been adopted in the recording of doses, care is needed in their interpretation, in particular when they are being compared with doses arising elsewhere. The information available to the Committee is generally not sufficient to allow the exercise of such care in interpreting recorded values.

23. For its previous assessments, the Committee adopted the convention that all quantitative results reported by monitoring services represent the average absorbed dose in the whole body (or the effective dose). It is further assumed that the dose from normal natural background radiation has been subtracted from the reported results, although this was not always clear from the responses to the questionnaire. It is also assumed that medical radiation exposures have not been included. The Committee recognized that it is almost always the reading from the dosimeter, suitably modified by calibration factors, that is reported, without considering its relationship to the absorbed doses in the various organs and tissues of the body or to the effective dose. This is still regarded as a reasonable convention, in particular as most data are for external exposure of the whole body to relatively uniform photon radiation of moderately high energy. Where exposure of the body is very non-uniform (especially in medical practice) or where exposure is mainly to low-energy radiation, the use of this convention may result in an overestimate of effective doses, which then needs appropriate qualification. Because the relationship between the reported dosimeter reading and the average absorbed dose in the whole body (or the effective dose) varies with the circumstances of the exposure, caution needs to be exercised when aggregating or directly comparing data from very dissimilar types of work. The reported data are appropriately qualified where the adoption of the above convention could lead to a significant misrepresentation of the actual doses.

3. Quantities for internal radiation exposure

24. Radionuclides taken into the body will continue to irradiate tissue until they have been fully excreted or have fully decayed. The committed effective dose for occupational exposure, E(50), is formally defined as the sum of the products of the committed organ or tissue equivalent doses and the appropriate organ or tissue weighting factors, where 50 is the integration time in years following intake. The committed equivalent dose, $H_T(50)$, is formally defined as the time integral of the equivalent dose rate in a particular tissue or organ that will be received by an individual following intake of radioactive material into the body, where 50 is, again, the integration time in years following intake.

25. In the calculation of E(50) and, where appropriate, of $H_T(50)$, the dose coefficient is frequently used. For occupational exposure, this is the committed effective dose per unit acute intake, e(50), or committed tissue equivalent dose per unit acute intake, $h_T(50)$, where 50 is the time period in years over which the dose is calculated. The unit is sievert per becquerel.

26. ICRP has recommended that the annual limit on intake (ALI) should be based on a committed effective dose of 20 mSv [I12]. The annual limit on intake (Bq) can then be obtained by dividing the annual average effective dose limit (0.02 Sv) by the dose coefficient, e(50) (Sv Bq^{-1}). The dose coefficients for occupational exposure for inhalation and ingestion of radionuclides based on the radiation and tissue weighting factors in ICRP Publication 60 [I12] and the new Human Respiratory Tract Model for Radiological Protection [I14] are given in ICRP Publication 68 [I15].

4. Total effective dose

27. The total effective dose, E(t), during any time period, t, can be estimated from the following expression:

$$E(t) = H_p(d) + \sum_j e_{j,inh}(50)\ I_{j,inh} + \sum_j e_{j,ing}(50)\ I_{j,ing}$$

where $H_p(d)$ is the personal dose equivalent during time period t at a depth d in the body, normally 10 mm for penetrating radiation; $e_{j,inh}(50)$ is the committed effective dose per unit activity intake by inhalation from radionuclide j, integrated over 50 years; $I_{j,inh}$ is the intake of radionuclide j by inhalation during time period t; $e_{j,ing}(50)$ is the committed effective dose per unit activity intake by ingestion from radionuclide j, integrated over 50 years; $I_{j,ing}$ is the intake of radionuclide j by ingestion during time period t.

28. The conversion coefficients for use in radiological protection against external radiation are given in ICRP Publication 74 [I16]. Except for radon progeny, values of the committed effective dose per unit intake for inhalation, $e_{j,inh}(50)$, and ingestion, $e_{j,ing}(50)$, are found in ICRP Publication 68 [I15], which takes account of the tissue

weighting factors in ICRP Publication 60 [I12] and the new lung model in ICRP Publication 66 [I14]. It is assumed that the data provided to the Committee will have been based on these conversion coefficients. The parameters for radon are given below.

5. Special quantities for radon

29. Special quantities and units are used to characterize the concentration of the short-lived progeny of both ^{220}Rn (commonly known as thoron) and ^{222}Rn (commonly known as radon) in air and the resulting inhalation exposure (see ICRP Publication 65 [I13]).

30. The potential alpha energy, ε_p, of an atom in the decay chain of radon or thoron is the total alpha energy emitted during the decay of this atom to ^{206}Pb or ^{208}Pb, respectively. The SI unit is joule, J; MeV is also used. The potential alpha energy concentration, c_p, of any mixture of short-lived radon or thoron decay products in air is the sum of the potential alpha energy of these atoms present per unit volume of air, and the SI unit is J m^{-3}. The potential alpha energy concentration can also be expressed in terms of the unit working level (WL), which is still used in some countries. One WL is defined as a concentration of potential alpha energy of 1.30 10^8 MeV m^{-3}. The potential alpha energy concentration can also be expressed in terms of the equilibrium equivalent concentration, c_{eq}, of the parent nuclide, radon. The equilibrium equivalent concentration for a non-equilibrium mixture of radon progeny in air is that activity concentration of radon in radioactive equilibrium with its short-lived progeny that has the same potential alpha energy concentration, c_p, as the non-equilibrium mixture. The SI unit of the equilibrium equivalent concentration is Bq m^{-3}.

31. The exposure of an individual to radon or thoron progeny is determined by the time integral of the potential alpha energy concentration in air or of the corresponding equilibrium equivalent concentration. In the former case, it is expressed in the unit J h m^{-3} and in the latter, in the unit Bq h m^{-3}. The potential alpha energy exposure is also often expressed in the historical unit working level month (WLM). Since this quantity was introduced for specifying occupational exposure, one month was taken to be 170 hours. Since 1 MeV = 1.602 10^{-13} J, the relationship between the historical and the SI unit is 1 WLM = 3.54 10^{-3} J h m^{-3}. The factor for converting from WLM to effective dose has been the subject of some debate. The Committee has adopted a radon dose coefficient of 9 nSv (Bq h m^{-3})$^{-1}$. However, the ICRP derived a conversion convention of 5 mSv (WLM)$^{-1}$ or 6 nSv (Bq h m^{-3})$^{-1}$, which was used in the questionnaire sent to national authorities in gathering information for the Annex. As a result of this difference, the data in this Annex for radon exposure situations underestimate the doses by about 30%.

B. MONITORING PRACTICES

32. For many reasons, worker monitoring practices differ from country to country, from industry to industry, and sometimes even from site to site within a given industry. Some of these differences stem from historical, technological, cost, or convenience considerations. In general, monitoring practice is such that more workers are individually monitored than is strictly necessary to meet regulatory requirements, with the consequence that only a fraction of those monitored receive measurable doses. Although these differences may not seriously affect the quality of the data, they could lead to some difficulties in making valid comparisons of results.

33. It is convenient to subdivide monitoring programmes into a number of categories. Routine monitoring is associated with continuing operations and is intended to demonstrate that the working conditions, including the levels of individual dose, remain satisfactory and meet regulatory requirements. This sort of monitoring is largely confirmatory in nature, but it underpins the overall monitoring programmes that should be undertaken to control occupational exposure. The most common type of routine monitoring is that undertaken using passive devices, such as film badges or TLDs. Such dosimeters are generally worn by personnel for a set period, and at the end of this period they are read and the doses recorded. In the main, the information used in this Annex comes from such monitoring programmes, although the approaches adopted and the degree of quality control exercised over the measurements vary from country to country.

34. To obtain a more up-to-date understanding of worker exposures, additional task-related monitoring is often undertaken. The intention of such monitoring is to provide data to support immediate decisions on the management of operations and optimization of protection. Task-related monitoring is usually based on some type of direct-reading dosimeter, such as a digital electronic dosimeter or a quartz-fibre electroscope, although multi-element TLD systems are also used. Some examples are given in this Annex.

35. Special monitoring may also be conducted when deemed necessary. It is investigative in nature and typically covers a situation in the workplace where insufficient information is available to demonstrate adequate control. It is intended to provide detailed information that will elucidate any problems and define future procedures.

36. ICRP indicates [I12] that three important factors should influence the decision to undertake individual monitoring: the expected level of dose or intake in relation to the relevant limits, the likely variations in the dose and intakes, and the complexity of the measurement and interpretation procedures that make up the monitoring programme. In practice, it is usual for all those who are occupationally exposed to external radiation to be individually monitored (i.e. to wear personal dosimeters). When doses are consistently low or predictable, other

methods of monitoring are sometimes used, as in the case of aircrew where doses can be calculated from flight rosters. The third factor results in an approach to the monitoring for external radiation that is different from that for intakes and the resulting committed effective dose.

1. External radiation exposure

37. The approach followed in many countries is to monitor the external radiation exposures of all individuals who work routinely in designated areas. However, on the basis of the recommendations of ICRP [I10], a distinction has often been made in monitoring programmes between those who can exceed 3/10 of the relevant dose limit and those who are most likely not to exceed. While individual monitoring may well have been carried out for those in the second category, the difference in monitoring lies largely in the degree of quality control that is exercised over the measurement. For the Committee, it is important to know whether doses to both groups of workers have been reported to it.

38. Monitoring programmes usually specify how and where personal dosimeters are to be worn to obtain the best estimate of effective dose or equivalent dose, as appropriate. In general, a dosimeter is placed on the front of the body. This is satisfactory provided that the dosimeters have been designed to measure $H_p(10)$.

39. Where lead aprons are used in medical radiology, different approaches have been adopted. In some cases, the assessment of effective doses to workers is carried out by means of a dosimeter worn on the trunk, under the apron. Where doses are likely to be significant, such as in interventional radiology, two dosimeters are sometimes used, one worn under the lead apron and the other worn outside. The purpose of the second dosimeter is to assess the contribution to the effective dose of irradiation of unshielded parts of the body [N6]. Where doses are low and individual monitoring is only intended to give an upper estimate of exposure, single dosimeters may have been worn outside the apron. Measurements made on phantoms using x-ray beams of 76 and 104 kVp have shown that estimates of the effective dose without the lead apron were within 20% of expected values; estimates with the dosimeter worn on the waist underneath the lead apron were lower than the expected values [M1]. The results suggest that accurate estimation of the effective dose from personal dosimeters under conditions of partial body exposure remains problematic and is likely to require the use of multiple monitors, which is not often done. Differing monitoring practices in medical radiology may therefore affect the validity of any comparisons of data acquired.

40. The choice of dosimeter will depend on the objectives of the monitoring programme and on the method of interpreting the data to be used. In practice, the basic choice for penetrating radiation has usually been between a dosimeter giving information on the personal dose equivalent at 10 mm depth and a discriminating device giving some indication of the types of radiation and their effective energies. For a wide range of energies, TLDs with detectors that exhibit little energy dependence of tissue dose response and are covered with tissue-equivalent filters of appropriate thicknesses are an example of the former. Multi-element dosimeters using either photographic film or thermoluminescent material, with filters of different atomic numbers and thicknesses, are an example of the second type.

41. The quality and accuracy of personal electronic dosemeters is improving rapidly, and in a few countries they have already been approved for formal dose assessment for some types of radiation to meet regulatory requirements. The approvals have tended to be limited to specific groups of workers [C2], but the pace of development is such that they are being considered as alternatives to photographic film and TLDs. They offer a low threshold limit of detection and a digital read-out.

42. Personal dosimeters that respond to neutrons over the complete energy range of interest are not available, and some of the current methods of assessment may be relatively expensive and time-consuming. Where the contribution to effective dose from neutrons is small compared with that from photons, the dose is sometimes determined by reference to the photon dose and an assumed ratio of the two components. Alternatively, use is made of measurements in the workplace environment and an assumed occupancy.

43. Monitoring for incident thermal and epithermal neutrons is performed using detectors with high intrinsic sensitivity to thermal neutrons (e.g. some TLDs) or detectors sensitive to other types of radiation (photons and charged particles) and a converter. Neutron interactions in the converter produce secondary radiations that are detectable by the dosimeter. The most common example of the latter technique is the film badge used with a cadmium filter. Some dosimeters have been designed such that they respond, in the main, to thermal and epithermal neutrons produced in the wearer's body by moderation and scatter of higher energy neutrons incident on the body. These "albedo" neutron dosimeters have good response characteristics up to 10 keV neutron energy and, by normalization appropriate to the workplace field, are used where the neutron personal dose equivalent is dominated by neutrons outside this energy range. The normalization process is critically dependent on the neutron spectrum, and if this is not well known or is variable, significant errors may result.

44. The assessment of personal dose equivalents from fast neutrons is carried out by means of nuclear emulsion detectors, bubble detectors, or track-etch detectors (e.g. poly-allyl diglycol carbonate, PADC). Nuclear emulsion dosimeters can measure neutrons at thermal energies and at energies above 700 keV. They have the disadvantages of being relatively insensitive to neutrons with intermediate energies and being sensitive to photons, and they suffer

from fading. Bubble detectors respond to fast neutrons from 100 keV upwards and have the advantage that they are direct-reading, non-sensitive to photons, and reusable, but they have the disadvantage of being temperature- and shock-sensitive. Track-etch detectors based on PADC respond to fast neutrons from about 100 keV upwards.

45. There is a highly complex relationship between the exposure to radiation and the effective dose. Models are required that are intended to give results that are not likely to underestimate the consequences of exposure, though without overestimating them excessively. This is the objective of the operational quantities.

46. In the workplace, the dose rate in air varies as a function of position and time. In the body, the equivalent dose in an organ or tissue is related to the dose equivalent at the surface by factors such as the type and quality of the radiation, the non-uniformity of the field, the orientation of the worker relative to the field, and the position and composition of the organs and tissues within the body. Several of these factors will be functions of both time and position in the workplace.

47. A dosimeter worn on the surface of the body is best regarded as a sampling device. It provides a measure of the dose equivalent to the skin and underlying tissue in the immediate vicinity of the dosimeter. A personal dosimeter on a phantom can be calibrated in terms of the measured or calculated values of the personal dose equivalent $H_p(d)$. When worn on the body of a person facing a unidirectional field of radiation, it will indicate the personal dose equivalent. Where a worker moves about the workplace, resulting effectively in a multidirectional field, a personal dosimeter will provide an adequate measure of the personal dose equivalent. Furthermore, the personal dose equivalents will, for most combinations of exposure, overestimate the effective dose. In some cases, the overestimation may be substantial.

48. There are three main areas of uncertainty in individual monitoring for external radiation:

(a) that which is inherent in dose calibrations;
(b) that due to the measurement of the operational quantity $H_p(10)$ as compared with the reading of an ideal dosimeter for the measurement of the quantity when worn on the same point on the body; and
(c) that which occurs if the dosimeter is not worn at the appropriate point on the body.

These uncertainties and how they are dealt with by the dosimetry services could also have an impact on the comparisons made in this Annex.

49. Many countries appear to follow the guidance given in ICRP Publication 35 [I10]. This defines acceptable uncertainties in routine monitoring for external radiation. Near the dose limits, the recommendation is that the uncertainty should be within a factor of 1.5 in either direction. Some relaxation is allowed at lower doses. It has been shown that these recommendations can be met by the majority of personal dosimeters currently in use, as far as the measurement of $H_p(10)$ is concerned [M2]. It must be appreciated, however, that the relationship between $H_p(10)$ and E introduces further errors, for example for photons. These are relatively small at higher photon energies (e.g. >0.5 MeV), but large overestimates can occur at lower energies, up to a factor of 5 at 10 keV.

2. Internal radiation exposure

50. There are three approaches to the determination of intake and internal dose:

(a) by quantification of exposure to radioactive materials in terms of their time-integrated air concentration via air sampling techniques;
(b) by the determination of internal contamination via direct *in vivo* measurements (*in vivo* methods include direct measurements used for assessing gamma and x-ray emitters and measurements of bremsstrahlung, by methods such as whole-body, thorax, skeleton, and thyroid counting); and
(c) by the measurement of activity in *in vitro* biological samples (*in vitro* methods are usually based on analysis of urine or faecal samples).

In practice, the approach adopted for a situation will depend on the abilities of the various options to indicate doses in that particular situation.

51. The choice between the three approaches is determined by the radiation emitted by the radionuclide; the biokinetic behaviour of the contaminant; its retention in the body, taking into account both biological clearance and radioactive decay; the required frequency of measurements; and the sensitivity, availability, and convenience of the appropriate measurement facilities. The most accurate method in the case of radionuclides emitting penetrating photon radiation is usually *in vivo* measurements. However, even when this method can provide information on the long-term accumulation of internal contamination, it may not be sufficient for assessing committed dose due to a single year's intake. The assessment may also need data from air monitoring. In many situations, therefore, a combination of methods is used. For radon dose assessments, however, air monitoring (individual or area) is the only available routine method.

52. There are two methods for the determination of exposure to airborne contamination:

(a) the use of representative/area air monitoring data, combined with a knowledge of occupancy of individual workers within each sampling area and an assumed breathing rate. This method is often used in situations where the more significant intakes are associated with well defined work activities; and
(b) the routine use of personal air samplers. This is often used where significant contributions to internal exposure are not linked to identifiable fixed locations.

53. Intakes of radioactive material are normally assessed routinely for workers who are employed in areas that are designated as controlled, specifically in relation to the control of contamination, and in which there are grounds for expecting significant intakes. However, there are difficulties in comparing data on internal doses in different countries because of the different approaches that are used to monitor and interpret the results. Measurements in a routine monitoring programme are often made at predetermined times not necessarily related to a particular intake event, and it is therefore necessary to make some assumptions about the pattern of intakes. Guidance on interpreting the results of measurements of intakes of radionuclides by workers was given in ICRP Publication 54 [I11]. This publication has been replaced, however, by a new document [I1] that uses current biokinetic models and is consistent with ICRP Publication 68 [I15]. In keeping with the ICRP advice, it is usual for the results of *in vivo* and *in vitro* monitoring measurements to be interpreted using the assumption that the intake took place at the mid-point of the interval between monitoring times. Assessment of doses from air sampling data requires knowledge of the physical and chemical properties of the radioactive materials, including the particle size and solubility in biological fluids. The current recommendation of ICRP [I15] is that a default value of 5 μm should be used for the particle size; previously, a value of 1 μm was recommended and may still be in use. A major difficulty in using area air sampling data to assess dose is whether the measurement data can be related to the activity concentration in the breathing zone. There is also the particular difficulty in interpreting area air sampling data when the contamination is due to localized sources or where only a few particles of radioactive material can represent a significant intake.

54. With the techniques currently available, it is generally not possible to obtain the same degree of precision in routine assessments of dose from intakes of radioactive material as is possible with external radiation. The dose assessment falls into three stages:

(a) individual monitoring measurements;
(b) assessment of intake from the measurements; and
(c) assessment of doses from the intake.

The overall uncertainty in the assessed dose will be a combination of the uncertainties in these three stages. A good example of the uncertainties involved and the relative merits of various dose assessment techniques is provided by a study of chronic low-level exposure of workers in nuclear fuel reprocessing [B3]. The study was able to compare assessments of intakes from static air sampling (SAS) and personal air sampling (PAS) and to then compare dose assessments from personal air sampling and biological *in vitro* samples. In the first of these comparisons, the dose assessed by personal air sampling was about an order of magnitude larger than that implied by static air sampling. For the group as a whole, over a seven-year period there was reasonable agreement between the geometric mean cumulative doses (23 mSv for biological sampling and 30 mSv for personal air sampling). However, there was a lack of correlation when viewed at any individual level, with no single identifiable factor to explain the difference. This must cast some doubt on the adequacy of personal air samplers for estimating annual intakes of individual workers at the levels of exposure encountered in operational environments.

55. In practice, there are relatively few occupational situations in which internal exposures to man-made sources of radiation are significant, and significant exposures have generally been decreasing. Exposures may still be significant in a number of situations, however: the handling of large quantities of gaseous and volatile materials such as tritium (e.g. in the operation of heavy-water reactors and in luminizing); reactor fuel fabrication; the handling of plutonium and other transuranic elements (e.g. in the reprocessing of irradiated fuel and in nuclear weapons production); and some nuclear medicine situations. Significant internal exposures to natural radionuclides can occur in the mining and processing of radioactive ores, particularly uranium ores but also some other materials with elevated levels of natural radionuclides (e.g. mineral sands). Significant exposure to radon can also occur in other mines, underground areas such as show caves (e.g. those that are open to tourists), and some aboveground workplaces not normally associated with radiation exposure.

C. DOSE RECORDING AND REPORTING PRACTICES

56. In most countries dose recording and reporting practices are governed by regulations and can be different for various categories of workers depending on their anticipated levels of exposure. Like monitoring practices, they vary from country to country and may significantly affect the reported collective doses. The most important differences arise from the following:

(a) the recording of doses less than the minimum detectable level (MDL);
(b) the measurement technique used, for example, TLD, film, or electronic dosimeter in the case of external radiation exposure;
(c) the assignment of doses to fill missing record periods;
(d) the treatment of unexpectedly high doses;
(e) the subtraction of background radiation doses;
(f) the protocol for determining who in the workforce should be monitored and for whom doses should be recorded in particular categories; and
(g) whether or not internal exposures are included or treated separately.

57. The recording level is the level above which a result is considered to be significant enough to be recorded, lower values being ignored [I12]. Recent advice from ICRP is

that the recording level for individual monitoring should be based on the duration of the monitoring period and an annual effective dose no lower than 1 mSv [I17]. In practice, little use is made of recording levels in individual monitoring for external radiation exposure, and many countries adopt the practice of recording all measured doses above the MDL for the technique used. When doses are determined to be less than the MDL, the value recorded may be zero, some pre-designated level, or the MDL itself. These differences affect the comparability of results. Furthermore, the MDL will vary with the device used. For example, the MDL associated with electronic dosimeters is generally much lower than that for film badges or TLDs. Electronic dosimeters have not been extensively used for the assessment of individual dose for record keeping purposes, but this situation is changing. This could lead to significant differences in the recording of low levels of external exposure. For instance, during the first four months of operation of an electronic dosimetry system at Sizewell B nuclear power plant in the United Kingdom, the monthly collective dose measured by film badges was higher by a factor of 20 than that measured by electronic dosimeters [R1]. It is therefore important to understand the implications of recording levels and different MDLs on the average individual dose and collective dose.

58. When dosimeters are lost or readings are otherwise not available, administrative procedures are then used in assigning doses to individual dose records. These are assumed doses to the workers for the appropriate period for which measurements are not available. A variety of procedures are used in determining the assigned dose. These include the assignment of the appropriate proportion of the annual limit for the period for which the dosimeter was lost; the assignment of the average dose received by the worker in the previous 12 months; and the assignment of the average dose received by co-workers in the same period. Some of these procedures can distort records significantly, particularly if large numbers of dosimeters are lost within a particular occupational group. Where this is the case, direct comparisons with other data may be invalid or, at least, need qualification. A similar situation may arise in the treatment of unexpectedly high measured doses that are considered not to be a true reflection of the actual doses received.

59. The background signal of a dosimeter involves contributions from both the non-radiation-induced signals from the dosimeter and the response of the dosimeter to natural background radiation. This signal is often subtracted from the actual dosimeter reading before recording. In many countries, the practice is to use a single value that takes account of the contributions to the background signal, that from natural background radiation being the average for the country as a whole. Where there are significant variations in the gamma-ray contribution from natural sources, this practice may have some influence on the individual doses that are recorded, particularly where the occupational exposures are similar in magnitude to those from the natural environment.

60. In the past, internal and external exposures were generally recorded separately. Furthermore, there were significant variations in the reporting levels for internal contamination, and this added to the difficulty of compiling meaningful statistical information. There is now increased emphasis on recording the sum of the annual effective dose from external irradiation and the committed effective dose from internal irradiation. Such data will enable more valid comparisons to be made of the radiological impact of different practices. However, comparisons of the more recent data with data for earlier periods will need to be treated with caution. For example, internal exposures in some occupations and industries (fuel fabrication and fuel reprocessing) may have been significant during the periods covered in previous assessments by the Committee but may not have been included in the data. Furthermore, inclusion of internal doses may result in an apparent step increase in the level of exposure received by workers in industries where internal exposure contributes significantly.

61. A major cause of difficulty in comparisons, particularly of average individual and collective doses, is the protocol used for determining who in the workforce is to be monitored and to have data recorded within any particular category. For instance, it is important to know whether the data for nuclear power operations include doses to visitors, administrative staff, and contract workers in addition to the company's employees.

62. In the UNSCEAR 1993 Report [U3], the advantage was noted of reporting data according to an agreed categorization scheme of work and also the difficulty of doing so, particularly in view of the differences in long-established national practices. The categories used by the Committee in this Annex are given in Table 1; there are some differences between this categorization and that used in the UNSCEAR 1993 Report. The main differences are that veterinary practice and educational establishments are now placed in a miscellaneous category, and there is some development of the section on natural radiation. However the approach adopted should still permit broad comparisons to be made with the data in the UNSCEAR 1993 Report. The dose monitoring and recording procedures for occupational exposure obtained from the UNSCEAR Survey of Occupational Radiation Exposures are given in Table 2. The data are not comprehensive for some of the attributes.

63. Any harmonization of the way data are recorded in various countries would help in future surveys. The European Union has an ongoing project, European Study of Occupational Exposure (ESOREX) [F3], to compare the administrative systems of the member states that are used for registering individual occupational exposure, to identify differences, and to analyse the possibility of harmonization within Europe. The project has also been extended to cover central and east European countries [F4].

D. CHARACTERISTICS OF DOSE DISTRIBUTION

64. Dose distributions are the result of many constraints imposed by the nature of the work, by management, by the workers, and by legislation. In some job categories it may be unnecessary for workers ever to receive more than very low doses, whereas in other jobs workers may have to be exposed to high doses fairly routinely. Management controls act as feedback mechanisms, especially when individual doses approach the annual dose limit, or some proportion of it, in a shorter period of time.

65. The Committee is principally interested in comparing dose distributions and in evaluating trends. For these purposes, it identified three characteristics of dose distributions as being particularly useful:

(a) the average annual effective dose (i.e. the sum of the annual dose from external irradiation plus the committed dose from intakes in that year), $\bar{E}$;
(b) the annual collective effective dose, S (referred to as M in some earlier UNSCEAR reports), which is related to the impact of the practice; and
(c) the ratio, SR_E, of the annual collective effective dose delivered at annual individual doses exceeding E mSv to the total collective dose. SR (referred to as MR in some earlier UNSCEAR reports) provides an indication of the fraction of the collective dose received by workers exposed to higher levels of individual dose. This ratio is termed the collective dose distribution ratio.

66. Another ratio, NR_E, of the number of workers receiving annual individual doses exceeding E mSv to the total monitored or exposed workforce, is reported in many occupational exposure statistics, often when the ratio SR_E is not provided. The more frequent reporting of the ratio NR_E is probably due to the ease with which it can be estimated. In the past, the Committee was somewhat concerned because of the ratio's potential sensitivity to how the size of the workforce is defined (those monitored, those measurably exposed, etc.); comparisons of values of this ratio for different occupations and in different countries would, in general, require some qualification. The ratio SR_E, on the other hand, is relatively insensitive to this parameter and is therefore a better means of affording fair comparisons between exposures arising in different industries or practices. Notwithstanding the limitations of the ratio NR_E, it is included in the characteristics reported by the Committee. This reflects its potential for use in more limited circumstances (e.g. when analysing trends with time in a given workforce or making comparisons between workforces that have been defined in comparable ways). The ratio SR_E, however, remains the most appropriate basis for comparing data generally.

67. The annual collective effective dose, S, is given by

$$S = \sum_{i=1}^{N} E_i$$

where E_i is the annual effective dose received by the ith worker and N is the total number of workers. In practice, S is often calculated from collated dosimetry results using the alternative definition

$$S = \sum_{j=1}^{r} N_j E_j$$

where r is the number of effective dose ranges into which the dosimetry results have been collated and N_j is the number of individuals in the effective dose ranges for which E_j is the mean annual effective dose. The average annual effective dose, $\bar{E}$, is equal to S/N. The number distribution ratio, NR, is given by

$$NR_E = \frac{N(>E)}{N}$$

where N(>E) is the number of workers receiving annual doses exceeding E mSv. The annual collective dose distribution ratio, SR, is given by

$$SR_E = \frac{S(>E)}{S}$$

where S(>E) is the annual collective effective dose delivered at annual individual doses exceeding E mSv.

68. The total number of workers, N, warrants further comment, as it has implications for the various quantities estimated. Depending on the nature of the data reported and subject to the evaluation (or the topic of interest), the number of workers may be those monitored, those classified, those measurably exposed, the total workforce, or some subset thereof. These quantities, therefore, will always be specific to the nature and composition of the workforce included in the estimation; when making comparisons, caution should be exercised to ensure that like is being compared with like. These aspects were discussed in Section I.C, where the implications of different monitoring and reporting practices for the assessed average individual and collective doses were identified. In this Annex, consideration is, to the extent practicable, limited to the estimation of the above quantities for the monitored and measurably exposed workforces; however, lack of uniformity between employers and countries in determining who should be monitored and/or what constitutes measurably exposed means that even these comparisons between ostensibly the same quantities are less rigorous than might appear. Where necessary, quantities estimated for a subset of the workforce (e.g. those measurably exposed) can be transformed to apply to the whole workforce; methods of achieving this, based on characteristics of the dose distributions, are discussed below.

69. In summary, the following characteristics of dose distributions will be considered by the Committee in this assessment of occupational exposures:

(a) the average annual effective dose (i.e. the sum of the annual dose from external radiation and the committed dose from intakes in that year), $\bar{E}$;

(b) the annual collective effective dose (i.e. the sum of the annual collective dose from external irradiation and the committed collective dose from intakes in that year), S;
(c) the collective dose distribution ratio, SR_E, for values of E of 15, 10, 5, and 1 mSv; and
(d) the individual dose distribution ratio, NR_E, for values of E of 15, 10, 5, and 1 mSv.

E. ESTIMATION OF WORLDWIDE EXPOSURES

70. Inevitably, the data provided in response to the UNSCEAR Survey of Occupational Radiation Exposures were insufficient for estimating worldwide levels of dose. Procedures were therefore developed by the Committee to derive worldwide doses from the data available for particular occupational categories. Two procedures were developed, one for application to occupational exposures arising at most stages in the commercial nuclear fuel cycle and the other for general application to other occupational categories.

71. In general, the reporting of exposures arising in the commercial nuclear fuel cycle is more complete than that of exposures arising from other uses of radiation. The degree of extrapolation from reported to worldwide doses is, therefore, less, and this extrapolation can be carried out with greater reliability than for other occupational categories. Moreover, worldwide statistics are generally available on capacity and production in various stages of the commercial nuclear fuel cycle. Such data provide a convenient and reliable basis for extrapolating to worldwide levels of exposure. Thus, the worldwide annual collective effective dose, S_w, from a given stage of the nuclear fuel cycle (e.g. uranium mining, fuel fabrication, or reactor operation) is estimated to be the total of annual collective effective doses from reporting countries times the reciprocal of the fraction, f, of world production (uranium mined, fuel fabricated, energy generated, etc.) accounted for by these countries, namely,

$$S_w = \frac{1}{f} \sum_{c=1}^{n} S_c$$

where S_c is the annual collective dose from country c and n is the number of countries for which occupational exposure data have been reported. The fraction of total production can be expressed as

$$f = \sum_{c=1}^{n} P_c \; / \; P_w$$

where P_c and P_w are the production in country c and in the world, w, respectively.

72. The annual number of monitored workers worldwide, N_w, is estimated by a similar extrapolation. Because the data are more limited, the worldwide distribution ratios, $NR_{E,w}$ and $SR_{E,w}$, are simply estimated as weighted averages of the reported data. The extrapolations to worldwide collective effective doses and numbers of monitored workers and the estimation of worldwide average distribution ratios are performed annually. Values of these quantities have been averaged over five-year periods, and the average annual values are reported in this Annex.

73. For occupational exposures to radiation from practices other than operations of the nuclear fuel cycle, statistics are not so readily available on the worldwide level of the practices or their distribution among countries. In these cases a simpler and, inevitably, less reliable method of extrapolation has to be used. A variety of approaches are possible (e.g. scaling by size of population, by employment in industrial or medical professions, or by some measure of industrial output). In the end, it seemed to be most practical and reasonable to extrapolate on the basis of GDP [U14]. Several considerations influence the choice of this quantity in preference to others, notably the availability of reliable worldwide statistics on GDPs and their potential for general application; the latter is a consequence of the expectation that GDP is reasonably correlated with both the level of industrial activity and medical care in a country, characteristics unlikely to be reflected in any other single quantity. To make the extrapolation more reliable, it is applied not globally but separately over particular geographic or economic regions, followed by summation over these regions. This results in extrapolations of available data within groups of countries with broadly similar levels of economic activity and allows for general geographical comparisons.

74. The worldwide annual collective effective dose for other uses of radiation, is estimated as

$$S_w = \sum_{r=1}^{m} S_r$$

where

$$S_r = \frac{1}{g_r} \sum_{c=1}^{n_r} S_c$$

where S_r is the annual collective effective dose in geographic or economic region r, n_r is the number of countries in region r for which occupational exposure data have been reported, m is the number of regions, and g_r is the fraction of GDP of region r, represented by those countries for which occupational exposure data are available and is given by

$$g_r = \sum_{c=1}^{n_r} G_c \; / \; G_r$$

where G_c and G_r are the GDPs of country c and region r, respectively.

75. The above equations are applied to estimate collective doses for those regions for which occupational exposure

data are available for at least one country within the region. For those regions for which no data for any country were reported, a modified approach for estimating regional collective dose is adopted:

$$S_r = G_r \sum_{c=1}^{n} S_c \; / \; \sum_{c=1}^{n} G_c$$

76. The annual number of monitored workers worldwide, N_w, is estimated by the same procedure. The worldwide distribution ratios are estimated as for operations of the nuclear fuel cycle, but the averaging is performed on a regional basis before summing over all regions. The number of measurably exposed workers worldwide, M_w, is estimated in a similar manner.

II. THE NUCLEAR FUEL CYCLE

77. A significant source of occupational exposure is the operation of nuclear reactors to generate electrical energy. This involves a complex cycle of activities, including the mining and milling of uranium, uranium enrichment, fuel fabrication, reactor operation, fuel reprocessing, waste handling and disposal, and research and development activities. Exposures arising from this practice were discussed and quantified in the UNSCEAR 1972 [U8], 1977 [U7], 1982 [U6], 1988 [U4], and 1993 [U3] Reports, with comprehensive treatment in the UNSCEAR 1977 and 1982 Reports. In comparison with many other sources of exposure, this practice is well documented, and considerable quantities of data on occupational dose distributions are available, in particular for reactor operation. This Annex considers occupational exposure arising at each main stage of the fuel cycle. As the final stage, treatment and disposal of the main solid wastes, is not yet sufficiently developed to warrant a detailed examination of potential exposures, it is given only very limited consideration. However, for the period under consideration, occupational exposures from waste disposal are not expected to significantly increase the sum of the doses from the other stages in the fuel cycle. For similar reasons, no attempt is made to estimate occupational exposures during the decommissioning of nuclear installations, although this will become an increasingly important stage.

78. Each stage in the fuel cycle involves different types of workers and work activities. In some cases, e.g. for reactor operation, the data are well segregated, while in others the available data span several activities, e.g. uranium mining and uranium milling. Where the data span a number of activities, this is noted in footnotes to the tables. The data on occupational exposures for each of the activities are derived primarily from the UNSCEAR Survey of Occupational Radiation Exposures but also from other sources, particularly the Information System on Occupational Exposure of the OECD/NEA [O4, O5].

79. For each stage of the fuel cycle estimates are made of the magnitude and temporal trends in the annual collective and average individual effective doses, the numbers of monitored workers, and the distribution ratios. The collective doses are also expressed in normalized terms, that is, per unit practice relevant to the particular stage of the cycle. For uranium mining and milling, fuel enrichment, fuel fabrication, and fuel reprocessing, the normalization is initially presented in terms of unit mass of uranium or fuel produced or processed; an alternative way to normalize is in terms of the equivalent amount of energy that can be (or has been) generated by the fabricated (or enriched) fuel. The bases for the normalizations, namely, the amounts of mined uranium, the separative work during enrichment, and the amount of fuel required to generate a unit of electrical energy in various reactor types, are given in Annex C, "*Exposures to the public from man-made sources of radiation*". For reactors, the data may be normalized in several ways, depending on how they are to be used. In this Annex, normalized collective doses are given per reactor and per unit electrical energy generated.

80. To allow proper comparison between the doses arising at different stages of the fuel cycle, all the data are ultimately presented in the same normalized form, in terms of the electrical energy generated (or the amount of uranium mined or fuel fabricated or reprocessed, corresponding to a unit of energy subsequently generated in the reactor), which is the output of the nuclear power industry. This form of normalization is both valid and useful when treating data accumulated over a large number of facilities or over a long time. It can, however, be misleading when applied to data for a single facility for a short time period; this is because a large fraction of the total occupational exposure at a facility arises during periodic maintenance operations, when the plant is shut down and not in production. Such difficulties are, however, largely circumvented in this Annex, since the data are presented in an aggregated form for individual countries and averaged over five-year periods.

81. Various national authorities or institutions have used different methods to measure, record, and report the occupational data included in this Annex. The main features of the method used by each country that responded to the UNSCEAR Survey of Occupational Radiation Exposures are summarized in Table 2. The potential for such differences to compromise or invalidate comparisons between data is discussed in Section I.A.3. The reported collective doses and the collective dose distribution ratios are largely insensitive to the differences identified in Table 2, so these quantities can generally be compared without further qualification. The average doses to monitored workers and the number distribution ratios are, however, sensitive to decisions and practice on who in a workforce is to be monitored. Differences in these areas could not be discerned from responses to the UNSCEAR Survey of Occupational Radiation Exposures, so

they cannot be discerned from Table 2. However, because the monitoring of workers in the nuclear power industry is in general fairly comprehensive, comparisons of the average individual doses (and number distribution ratios) reported here are judged to be broadly valid. Nonetheless, it must be recognized that differences in monitoring and reporting practices do exist, and they may, in particular cases, affect the validity of comparisons between reported data; to the extent practicable, where such differences are likely to be important they are identified.

A. URANIUM MINING AND MILLING

82. Uranium is used for military, commercial, and research purposes. It is widely distributed in the earth's crust, and mining is undertaken in over 30 countries [O3]. Commercial uranium use is primarily determined by the fuel consumption in nuclear power reactors and nuclear research reactors and by the inventory requirements of the fuel cycle. Uranium requirements for power reactors continue to increase steadily, while the requirements for research reactors remain modest by comparison. The annual production of uranium in various countries in the years 1990–1997 is given in Annex C, "*Exposures to the public from man-made sources of radiation*", and more detailed information can be found in an OECD/NEA publication [O3].

83. The mining of uranium is similar to that of any other material. It mainly involves underground or open-pit techniques to remove uranium ore from the ground, followed by ore processing, usually at a location relatively near the mine. The milling process involves the crushing and grinding of raw ores, followed by chemical leaching, separation of uranium from the leachate, precipitation of yellowcake [K4], and drying and packaging of the final product for shipment. In response to the declining price of uranium, the emphasis in recent years has been on lower-cost methods for extracting uranium [O3]. The percentage of conventional underground mining was reduced from about 55% to about 45% from 1990 to 1992. The lower-cost methods are open-pit mining, *in situ* leaching, and by-product production (e.g. from the mining of other minerals such as gold). The percentage from conventional open-pit mining increased during this period, from 38% to 44%; that from *in situ* leaching from 5.7% to 9.1%; and that from by-product production from 1.1% to 2.2%. In 1992, there were 55 operating uranium mines in the world in over 21 countries, with 32% of the production coming from Canada alone. About 84% of the world's production came from only 12 countries: Australia, Canada, France, Kazakhstan, Kyrgyzstan, Namibia, Niger, the Russian Federation, South Africa, Tadjikistan, Uzbekistan, and the United States [G2] (see Table 28 of Annex C, "*Exposures to the public from man-made sources of radiation*", for annual production of uranium in other years between 1990 and 1997).

84. The mining and milling of uranium ores can lead to both internal and external exposures of workers. Internal exposure may arise from the inhalation of radon gas and its decay products and radionuclides in ore dust. The extent of internal exposure will depend on many things, including the ore grade, the airborne concentrations of radioactive particles (which vary depending on the type of mining operation and the quality of ventilation), and the particle size distribution. In underground mines, the main source of internal exposure is likely to be radon and its decay products. Because of the confined space underground and practical limitations to the degree of ventilation that can be achieved, the total internal exposure is of greater importance in underground mines than in open-pit mines. In open-pit mines, the inhalation of radioactive ore dusts is generally the largest source of internal exposure, although the doses tend to be low. Higher doses from this source would be expected in the milling of the ores and production of yellowcake.

85. With the emphasis on low-cost uranium production, new projects are expected to focus on high-grade unconformity and sandstone-type deposits. These may be amenable to *in situ* leaching techniques, but where underground mining is used, exposures of workers are likely to continue to be of concern. In future surveys there will be a need to consider the exposures that arise during the rehabilitation of old mining operations. For example in Germany, where uranium mining is no longer undertaken, annual exposures to workers due to the removal of uranium mining residues are estimated for 1995 to be distributed as follows: 1–6 mSv, 1,250 workers; 6–20 mSv, 230 workers; and >20 mSv, no workers [S2]. The exposures result from external radiation, inhalation of radioactive dust particles, and inhalation of radon progeny.

86. Exposure data for mining and milling of uranium ores from the UNSCEAR Survey of Occupational Radiation Exposures for 1990–1994 are given in Tables 3 and 4, respectively; and trends for the four periods from 1975 are given in Figure II. The questionnaire asked respondents to use a conversion factor for exposure to radon decay products of 5 mSv per WLM, the value recommended by ICRP [I12].

87. Over the three previous five-year periods the average annual amounts of uranium mined worldwide were 52, 64, and 59 kt, a reasonably constant level of production, with by far the largest part mined underground. As has already been mentioned, there has more recently been a move away from underground mining and a reduction in the amount mined. For the 1990–1994 period, the average annual amount mined was 39 kt, a reduction of about one third. The year-on-year figures showed a steady downward trend, from 49.5 kt in 1990 to 31.6 kt in 1994. During this period a number of countries, including Bulgaria, Germany, and Slovenia, reported that mining operations had ceased, although some exposures continued from measures to treat the closed-down mining operations. These trends would be expected to affect both the magnitude of the collective doses and the dose profiles, and indeed they do so.

88. The data set for 1990–1994 is smaller than for the preceding period, 1985–1989, with data from 10 countries as

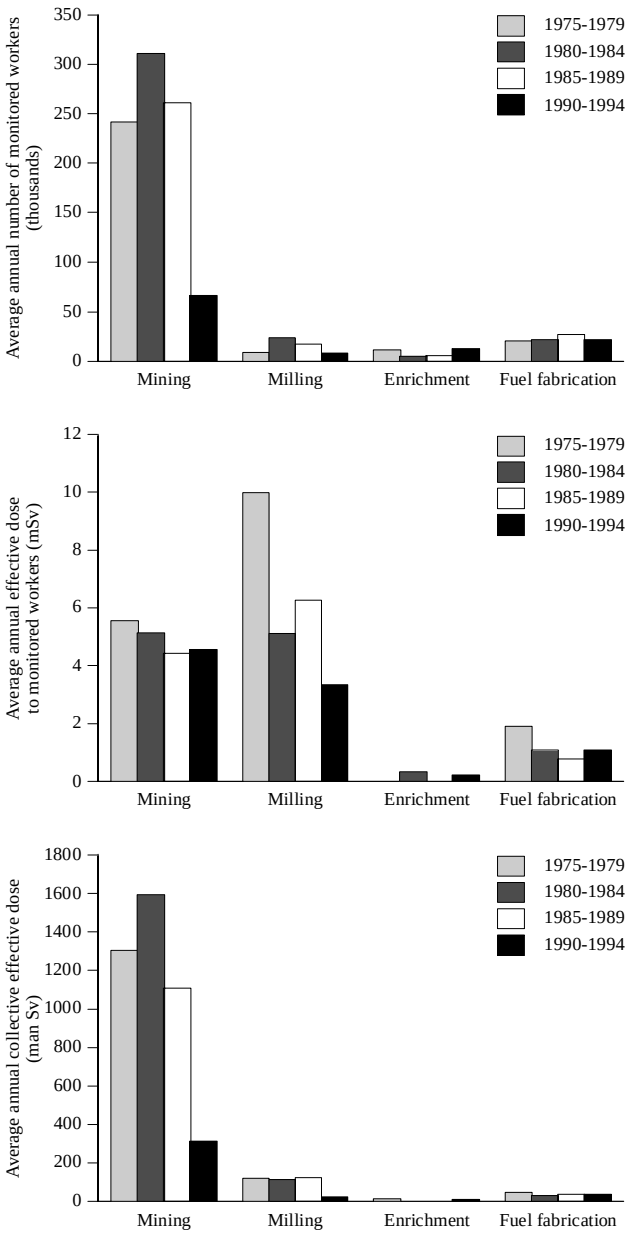

Figure II. Trends in numbers of monitored workers, doses to workers, and collective doses for mining, milling, enrichment and fuel fabrication.

opposed to 14 countries, respectively. The 1985–1989 data were dominated by underground mining data from South Africa, which accounted for some 70% (82,000) of the total reported monitored workers (114,000) and 55% (278 man Sv) of the reported collective dose (507 man Sv). China also made an important contribution to the 1985–1989 data, with a reported collective dose of 114 man Sv, some 22% of the total reported. The lack of data for 1990–1994 from South Africa and China (and, to a lesser extent, from India and the United States) distorts any extrapolation to arrive at a world figure. For the earlier periods the extrapolation for the number of monitored workers and collective dose worldwide was based on the ratio between the total amount of ore produced by the reporting countries and total world production. Employing the same approach to the 1990–1994 period would give a worldwide monitored population of 28,000 and an average annual collective effective dose of 140 man Sv. Both of these estimates are an order of magnitude less than for 1985–1989. The Committee regarded this as a significant underestimate and has instead chosen to make estimates for those countries that had not reported for 1990–1994 but that did report for 1985–1989, before extrapolating on the basis of worldwide production of uranium ore. This approach has the benefit of ensuring that major contributors such as South Africa and China are more adequately accounted for. The estimates for these countries (shown in square brackets in Table 3) are based on the average trends for countries reporting for both 1985–1989 and 1990–1994 and take into account the best estimates of uranium ore production. On this basis, the average annual number of monitored workers worldwide fell from 260,000 in 1985–1989 to 69,000 in 1990–1994. For the previous two periods the numbers had been 240,000 and 310,000. This reduction by a factor of 3 or 4 is also seen in the values for average annual collective effective doses. For the three previous periods the worldwide estimates were 1,300, 1,600 and 1,100 man Sv, but for 1990–1994 the value was 310 man Sv. Similarly, the average collective dose per unit of uranium extracted had been 26, 23, and 20 man Sv per kt for the three previous periods and was down to 7.9 man Sv per kt for 1990–1994; the corresponding values for average collective dose per unit energy were 5.7, 5.5, and 4.3 man Sv per GWa, falling to 1.7 man Sv per GWa for 1990–1994 (see Figure III). However, the estimated average annual effective dose, 4.5 mSv, was marginally higher than for the immediately preceding period, when it was 4.4 mSv. With the doses from underground mining dominating the collective dose and the known difficulties in reducing individual doses, the data would be consistent with a worldwide reduction in underground mining activity coupled with more efficient mining operations.

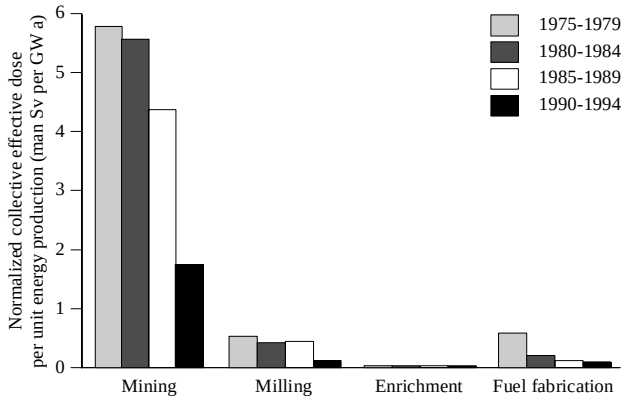

Figure III. Normalized collective effective dose per unit energy production for mining, milling, enrichment and fuel fabrication.

89. Data on exposure to workers from uranium milling were provided from only two countries, Australia and Canada, and are given in Table 4. In line with their reductions in mining, both countries show significant reductions in the number of monitored workers and the collective dose. It is difficult to extrapolate worldwide from these data, but crude estimates can be made. As in previous

UNSCEAR reports it is assumed that the amount of uranium milled is equal to the amount mined. The combined data for the two countries reporting show a reduction by a factor of about 4 in the average annual collective dose and about a factor of 2 in the number of monitored workers relative to 1985–1989. These factors are in line with the trends for uranium mining, and it would seem appropriate to apply them to derive worldwide estimates for 1990–1994. Doing so leads to worldwide estimates for average annual monitored workers of 6,000 compared with 12,000, 23,000, and 18,000 in each of the three previous periods; to an average annual collective effective dose of 20 man Sv compared with 124, 117, and 116 man Sv in each of the three previous periods; and to an average annual effective dose of 3.3 mSv compared with 10.1, 5.1, and 6.3 mSv in each of the three previous periods.

B. URANIUM ENRICHMENT AND CONVERSION

90. Uranium conversion is the process by which UO_2, which is the chemical form of uranium used in most commercial reactors, is produced for the fabrication of reactor fuel. In reactors that use fuel slightly enriched in ^{235}U (generally about 3%; natural uranium contains about 0.7% ^{235}U), uranium from the milling process must be enriched before fuel fabrication. Thus, the U_3O_8 from the milling process is converted to UO_2 by a reduction reaction with H_2. The UO_2 is then converted to UF_4 by the addition of hydrofluoric acid (HF), and then to UF_6 using fluorine (F_2). This gaseous product, UF_6, is then enriched in ^{235}U. Most of this was done by the gaseous diffusion process, but increasingly, gaseous centrifuge techniques are being used. Once the enrichment process has been completed, the UF_6 gas is reconverted into UO_2 for fuel fabrication. Occupational exposures occur during both the conversion and enrichment stages, with, in general, external radiation exposure being more important than internal radiation exposure. Workers may, however, be exposed to internal radiation, particularly during maintenance work or in the event of leaks.

91. During 1990–1994 most enrichment services came from five suppliers: Department of Energy (United States), Eurodif (France), Techsnabexport (Russian Federation), Urenco (Germany, Netherlands and United Kingdom) and China. (Entities in those same countries, plus Canada, offered services for the conversion process that precedes enrichment.) The enrichment capacity of these and a few other small producers has been estimated at between 32 and 35 million separative work units (MSWu) per annum during 1990–1994 compared with demand of between 23 and 27 MSWu [O8, O9]. Exposure data for 1990–1994 are given for Canada, France, Japan, the Netherlands, South Africa, the United Kingdom, and the United States in Table 5. With three exceptions the data are for enrichment by the diffusion process; the exceptions are South Africa, where the helicon enrichment process has been used, and the United Kingdom and Japan, where centrifuge enrichment is used. It is not possible to compare the two time periods because data from the United States dominated the 1985–1989 set, and the 1990–1994 set reflects an important contribution from Canada as well as a significant increase in the South African data. Based on reported data, the annual collective effective dose increased from 0.43 man Sv to 0.79 man Sv, and the resultant average dose per monitored worker increased from 0.08 mSv to 0.14 mSv. However, it should be noted that the values for 1985–1989 were somewhat lower than for earlier periods.

92. Sums or averages of reported data are given in Table 5; however, because data on the separative work used in uranium enrichment are incomplete, an extrapolation based on size of the practice to estimate worldwide doses cannot be made. The alternative extrapolation, based on GDP, would also be inappropriate in this case, because enrichment is carried out in only a few countries. Accordingly, worldwide doses can be estimated only roughly.

93. The data for the five-year periods before 1990–1994 were dominated by the data from the United States, which accounted for some 80% of the collective dose estimates. Although the United States did not report data for 1990–1994, the totals increased. The average annual number of monitored workers increased from 5,000 to 12,600 between the last two reporting periods, and the average annual collective dose increased from 0.43 to 1.28 man Sv. The average annual effective dose to monitored workers was low, 0.10 mSv, in 1990–1994 and comparable to the value of 0.08 mSv for the preceding period. The absence of data from the Russian Federation and China would suggest that these figures are underestimates; but probably only by a factor of 2 or 3. Even taking this into account, the individual and collective doses from enrichment are small. Consequently, despite the major uncertainties in estimating worldwide exposures from this source, it would be appropriate to accept (as was done in the UNSCEAR 1993 Report) the reported data as being indicative of the worldwide figure. This will have little impact on the reliability of the estimated exposure from the whole of the nuclear fuel cycle.

C. FUEL FABRICATION

94. The characteristics of fuels that are relevant here are the degree of enrichment and the form, either metallic or oxide. The majority of reactors use low enriched fuel (typically a few percent of ^{235}U); the main exceptions are the gas-cooled Magnox reactors and the heavy-water-cooled and -moderated reactors, which use natural uranium. Some older research reactors use highly enriched uranium (up to 98%); however, for security reasons this material is used less and less. The four types of uranium fuel are unenriched uranium metal fuel, used in Magnox reactors; low enriched uranium oxide fuel, used in advanced gas-cooled, graphite-moderated reactors (AGRs) and in light-water-moderated and -cooled reactors (LWRs); unenriched oxide fuel is generally used in heavy-water-

cooled and -moderated reactors (HWRs); and mixed uranium/plutonium oxide (MOX) fuel used in LWRs and in fast breeder reactors (FBRs). The principal source of exposure during fuel fabrication is uranium (after milling, enrichment, and conversion, most decay products have been removed). This can lead to external exposure from gamma rays and intake of airborne activity.

95. The reports for the first period (1977–1979) in the UNSCEAR 1982 Report [U6] and for the second period (1980–1984) in the UNSCEAR 1988 Report [U4] considered exposures from fuel fabrication and uranium enrichment as one category. The UNSCEAR 1993 Report [U3] (for 1985–1989) considered the two categories separately and also carried out a detailed analysis by fuel type. In devising the UNSCEAR Survey of Occupational Radiation Exposures for 1990–1994, it was concluded that for this review a single category for fuel fabrication, separate from fuel enrichment and conversion, would be appropriate. The data from the UNSCEAR Survey of Occupational Radiation Exposures are given in Table 6.

96. The worldwide production of fuel increased steadily over the four five-year periods being 3.6, 6.1, 9.6 and 11.3 kt from first to last, as did the corresponding equivalent energy figures, 60, 100, 180, and 210 GWa. In all periods the production of fuel for LWRs dominates. Worldwide estimates of the average annual collective effective dose and the average annual number of monitored (and measurably exposed) workers have been obtained by scaling the sum of the reported data by the ratio of the fuel fabricated worldwide to that fabricated in those countries reporting data. A number of approximations had to be made in this extrapolation process owing to the absence of adequate data on the production of fuel worldwide and in some major producing countries. Annual fuel production in these cases was assumed to be equal to the production that would have been required for the generation of electrical energy by the reactors in that country. This method of extrapolation is the same as that used in the UNSCEAR 1993 Report [U3]. The data were taken from OECD and IAEA reviews [I2, I21, O8, O9], and the Committee's estimates are given in brackets in Table 6. The fact that some countries export or import fuel inevitably introduces a degree of uncertainty into the figures, so comparisons between periods and between countries should be treated with caution.

97. The average annual number of monitored workers has been reasonably constant over the four periods at about 20,000 but with a small peak of 28,000 in the 1985–1989 period. The worldwide average annual number of measurably exposed workers for 1990–1994 was approximately 11,000, about half the number of monitored workers. This is the first period for which a reasonable estimate has been possible. The estimated average annual collective dose showed a decline, from 36 to 21 man Sv, between the first two five-year periods but subsequently varied little, with the value for 1990–1994 being approximately 22 man Sv. The average annual effective dose to monitored workers showed an initial decline from 1.8 mSv to 1.0 mSv between the first two periods, and the value for 1990–1994, 1.03 mSv, is very similar to that for 1980–1984. The value of 0.78 mSv for 1985–1989 reflects the estimate of the number of monitored workers, which may have been an overestimate. While the collective dose has remained reasonably constant, it has done so against a background of increasing fuel fabrication; consequently, the normalized collective dose per kt of fuel and per unit energy has fallen, from 10.0 to 1.9 man Sv per kt fuel and from 0.59 to 0.10 man Sv per GWa.

D. REACTOR OPERATION

98. The types of reactor used for electrical energy generation are characterized by their coolant system and moderator: light-water-moderated and -cooled pressurized or boiling water reactors (PWRs, BWRs), heavy-water-moderated and -cooled reactors (HWRs), gas-cooled, graphite-moderated reactors (GCRs) in which the gas coolant, either carbon dioxide or helium, flows through a solid graphite moderator, and light-water-cooled, graphite-moderated reactors (LWGRs). These are all thermal reactors in which the moderator material is used to slow down fast fission neutrons to thermal energies. Fast breeder reactors (FBRs) make only a minor contribution to energy production at the present time. From 1990 to 1994, the number of operating reactors remained relatively stable, increasing slightly from 413 to 432 by the end of the period, with an annual average of 421. A listing of nuclear reactors in operation during 1990–1997, the installed capacities, and electrical energy generated is given in Annex C, "*Exposures to the public from man-made sources of radiation*". At the end of 1997, there were 437 nuclear power reactors operating in the world, with a capacity of about 352 GWe (net gigawatts electric) [I2]. They now supply about 17% of the total electrical energy generated in the world and account for about 6% of the world's total energy consumption.

99. In addition to data acquired in the UNSCEAR Survey of Occupational Radiation Exposures, data on exposures of workers at nuclear power reactors are also available from the database of OECD/NEA [O4, O5]. This database, known as the Information System on Occupational Exposure (ISOE), was begun in 1990 and involves a growing number of countries, including those from outside OECD, whose data are provided through the IAEA. The programme has been designed to provide an exchange of information on techniques and experience for assessing exposure trends, comparison of practices and results, and as low as reasonably achievable (ALARA) analyses. The ISOE data on occupational exposures at nuclear power reactors for 1990–1994 [L5] and data from the UNSCEAR Survey of Occupational Radiation Exposures for the various types of reactors are given in Table 7.

100. Occupational exposures can vary significantly from reactor to reactor and are influenced by such factors as reactor

size, age, and type. Several different broad categories of reactor are currently in operation, including PWRs, BWRs, GCRs (which include older Magnox reactors as well as a newer generation of reactors, advanced gas-cooled reactors (AGRs), HWRs, and LWGRs. Within each category, much diversity of design and diversity in the refuelling schedule can be seen, which may contribute to differences in occupational exposures. In addition, changes in operating circumstances can alter the exposure at the same reactor from one year to the next. Some of these variations will be elaborated upon in this Section.

101. Over 300 reactors (three quarters of the total number) presently operating in the world are light-water reactors (LWRs), either PWRs or BWRs. Of these, the PWRs are more common (70% of LWRs). HWRs have been developed particularly in Canada and are also used in Argentina, India, and the Republic of Korea. GCRs have been used particularly in the United Kingdom. LWGRs have been developed and used in the countries of the former USSR.

102. The type of reactor is just one determinant of the doses received by workers at reactors. Other basic features of the reactor play a role, including the piping and shielding configuration, fuel failure history, reactor water chemistry, and the working procedures and conditions at the reactor. All of these can differ from site to site, even among reactors of the same type, contributing to the differences seen in occupational exposures. At all reactors, external irradiation by gamma rays is the most significant contributor to occupational exposures. The exposures occur mostly during scheduled maintenance and/or refuelling outages. For the most part, such exposures are due to activation products (^{60}Co, ^{58}Co, ^{110m}Ag); however, when fuel failures occur, fission products (^{95}Zr, ^{137}Cs) may also contribute to external exposures. At BWRs, workers in the turbine hall receive some additional external exposure caused by ^{16}N, an activation product with an energetic gamma ray that is carried by the primary circulating water through the turbines. In HWRs, heavy water is used as both coolant and moderator. Neutron activation of deuterium produces a significant amount of tritium in these reactors, so in addition to the usual external exposures, workers may also receive internal exposures from tritium.

103. Throughout the world, occupational exposures at commercial nuclear power plants have been steadily decreasing over the past decade, and this trend is reflected in data for 1990–1994. Regulatory pressures, particularly after the issuance of ICRP Publication 60 [I12] in 1991, technological advances, improved plant designs, installation of plant upgrades, improved water chemistry and improved plant operational procedures and training, and the involvement of staff in the control of their own doses have all contributed to this decreasing trend. In Europe, the European ALARA Newsletter is a good example of the way in which information on reducing individual and collective doses can be disseminated among both operators and regulators. A newsletter with a similar objective had been put out for many years by the Brookhaven National Laboratory in the United States. The newsletters may also contain assessed data on occupational exposures.

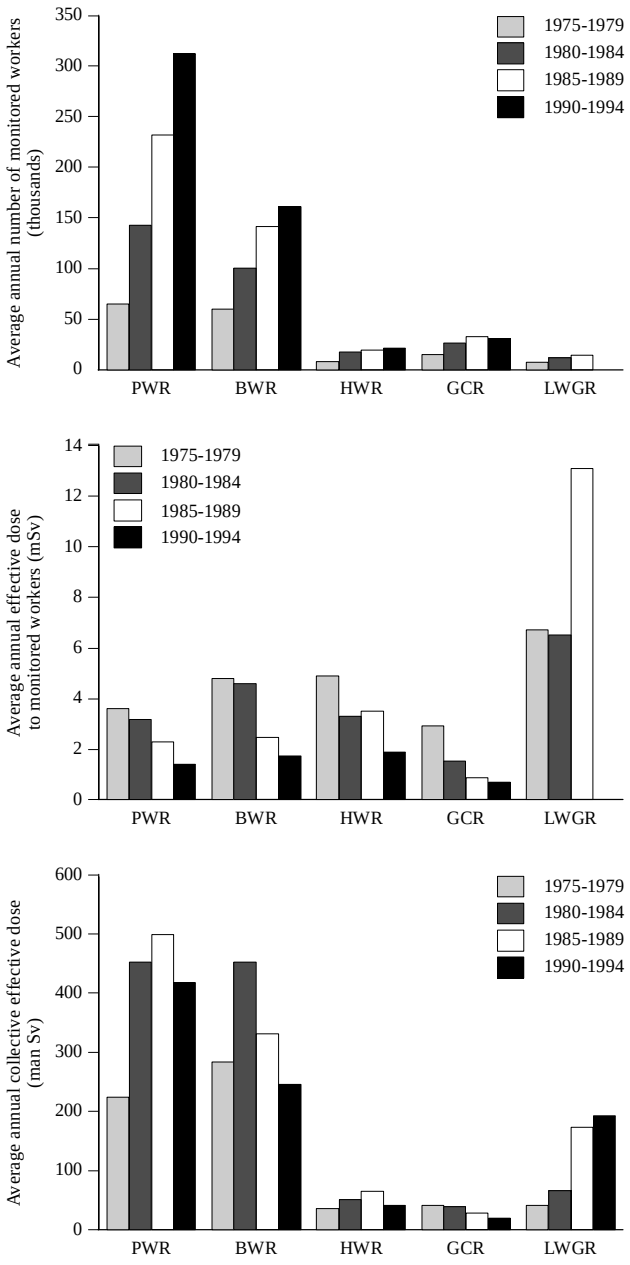

Figure IV. Trends in numbers of moinitored workers, doses to workers, and collective doses for reactor operation.

104. Data on occupational exposures at reactors of each type are detailed by country in Table 7 and a worldwide summary by reactor type is given in Table 8. Worldwide levels of exposure have been estimated from reported data; the extrapolations are based on the total energy generated in countries reporting data. Very little extrapolation was needed, as the reported data were substantially complete (about 85% for PWRs, 95% for BWRs, 80% for HWRs, 100% for GCRs, and 60% for LWGRs). The annual data reported in response to the UNSCEAR Survey of Occupational Radiation Exposures have been averaged over five-year periods, and Figures IV and V illustrate some of the trends. Previous UNSCEAR reports treated fast breeder reactors (FBRs) and high-temperature graphite reactors (HTGRs) separately. No

data were provided on these in the UNSCEAR Survey of Occupational Radiation Exposures, and in the main these types of facilities are no longer operational. The UNSCEAR 1993 and 1988 Reports [U3, U4] concluded that they make a negligible contribution to occupational exposure, so they are not considered further.

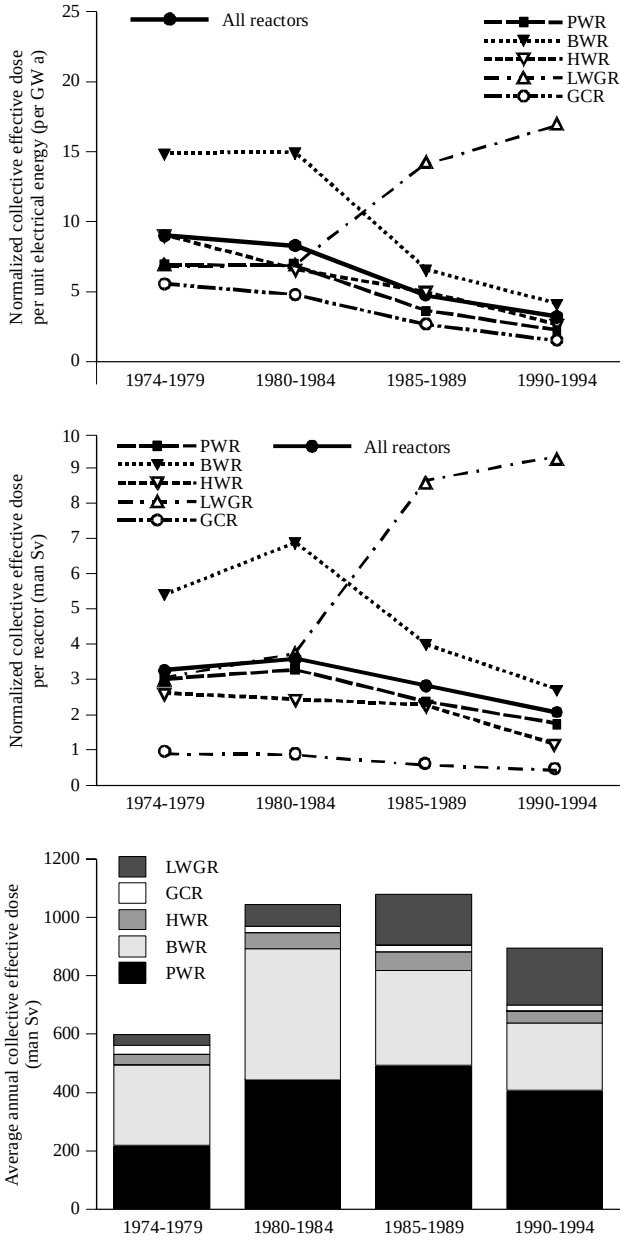

Figure V. Trends in collective effective dose for reactor operation and normalized collective effective dose per reactor and per unit electrical energy.

105. The UNSCEAR 1993 Report [U3] identified the need for more data on measurably exposed workers, as this provides a better basis for comparisons of average doses to individuals than is possible using the monitored worker data. The UNSCEAR Survey of Occupational Radiation Exposures shown in Table 7 now provides good data on measurably exposed workers for PWRs, BWRs, and HWRs. The vast majority of the GCRs are in the United Kingdom, and while data matching the definition of measurably exposed are not readily available, a good data set showing dose distribution is available from the United Kingdom's Central Index of Dose Information (CIDI) [H2].

106. There remain some difficulties in interpreting and ensuring fair comparisons between the various statistics. These difficulties were discussed in general terms in Section I.A, where a number of cautionary remarks were made. Three more specific observations need to be made in the present context. First, differences exist in the protocols adopted in various countries regarding the fraction of the workforce that is included when evaluating average annual individual doses; in some cases, only measurably exposed individuals are included, whereas generally the whole of the monitored workforce is taken into account. To the extent practicable, a clear distinction is maintained throughout this Annex between the average individual doses evaluated in the different ways. The use of different protocols for determining who in the workforce should be monitored is, however, a further confounding factor. Particular care must therefore be exercised when comparing average individual doses to ensure that the comparisons are made on equal grounds. These differences do not, however, materially affect the estimation or the comparison of collective doses, at least not within the inherent uncertainties associated with their evaluation.

107. Secondly, the procedures for the recording and inclusion of doses received by transient or contract workers may differ from utility to utility and country to country, and this may influence the respective statistics in different ways. In some cases, transient workers may appear in the annual statistics for a given reactor several times in one year (whereas they should appear once only, with the summed dose being recorded); if appropriate corrections are not made, then statistics so compiled will inevitably overestimate the size of the exposed workforce and underestimate the average individual dose and also the fractions of the workforce and the collective dose arising from individual doses greater than the prescribed levels. This will only be important where extensive use is made of transient workers.

108. Thirdly, countries differ in how they report the exposures of workers at nuclear installations. The majority present statistics for the whole workforce, i.e. employees of the utility and contract workers, often with separate data for each category; some report data for utility employees only, whereas others present the collective dose for the total workforce but individual doses for the utility workers only. Where necessary and practicable, the reported data have been adjusted to enable them to be fairly compared with other data; these adjustments are indicated in the respective Tables.

1. Light-water reactors

109. LWRs comprise a majority (about 60%) of the installed nuclear generating capacity. About 70% of them are PWRs and about 30% are BWRs. About 33% of the

LWRs are installed in the United States and about 18% in France, with the remainder distributed among some 20 countries. Experience has shown significant differences between occupational exposures at PWRs and those at BWRs. Each type is therefore considered separately.

(a) PWRs

110. External gamma radiation is the main source of exposure in PWRs. Since there is in general only a small contribution from internal exposure, it is only rarely monitored. The contribution of neutrons to the overall level of external exposure is insignificant. Most occupational exposures occur during scheduled plant shutdowns, when planned maintenance and other tasks are undertaken, and during unplanned maintenance and safety modifications. Activation products and to a lesser extent fission products within the primary circuit and coolant are the main source of external exposure. The materials used in the primary circuit, the primary coolant chemistry, the design and operational features of the reactor, the extent of unplanned maintenance, etc. all have an important influence on the magnitude of the exposure from this source; the significant changes that have occurred with time in many of these areas have affected the levels of exposure. One of the most important non-standard maintenance operations associated with significant dose is the replacement of steam generators. Data on the collective doses associated with this operation have been collected by OECD [O5] and are given in Table 9.

111. The average worldwide number of PWRs increased from 78 in 1975–1979 to 242 in 1990–1994. The corresponding increase in average annual energy generated has been somewhat greater, from 27 to 149 GWa. The number of monitored workers in PWRs increased from about 60,000 to 310,000 (see Figure IV). Between the first two periods the annual average collective effective dose increased by a factor of about 2, from 220 to 450 man Sv. A further small increase to 500 man Sv occurred in the third period, but the fourth period has seen a reduction to 415 man Sv. To see the underlying trend in the efficiency of protection measures from both design and operational procedures it is more instructive to look at the normalized collective dose. Per reactor this increased from 2.8 to 3.3 man Sv over the first two periods but has since dropped, through 2.3 to 1.7 man Sv per reactor. The corresponding values for collective effective dose per unit energy generated (man Sv $(GW\ a)^{-1}$) are (in chronological order) 8.1, 8.0, 4.3, and 2.8, a substantial decrease.

112. The average annual effective dose to monitored workers over the five-year periods has consistently fallen, from 3.5 to 3.1 to 2.2 to 1.3 mSv, an almost threefold reduction overall. For the first time a worldwide estimate of average annual effective dose to measurably exposed workers has been possible; the value of 2.7 is higher by a factor of about 2 than that for monitored workers. The dose distribution data also parallels the downward trend in doses, with both NR_{15} and SR_{15} consistently dropping; the values for 1990–1994 are <0.01 and 0.07, respectively.

113. There is considerable variation about the worldwide average values in both the trends and levels of dose in individual countries. In some cases this variation reflects the age distribution of the reactors and the build-up of activity in the cooling circuits. In other cases the reason for it is less obvious. More detailed analysis is contained in the various OECD reports [O2, O3, O4, O5].

(b) BWRs

114. External irradiation is also the main source of occupational exposure in BWRs, with most exposures arising during scheduled shutdowns, when planned maintenance is undertaken, and during unplanned maintenance and safety modifications. By far the largest number of BWRs are located in the United States and Japan.

115. Worldwide, the average number of BWRs increased from about 51 in 1975–1979 to about 90 in 1990–1994; the corresponding increase in the average annual energy generated worldwide was somewhat greater, from about 15 to 50 GWa. On average, 40% of this energy was generated by BWRs in the United States and 25% of it by BWRs in Japan. The number of monitored workers in BWRs worldwide increased from about 60,000 to about 160,000 over the period (Figure IV). The average annual collective effective dose increased from about 280 to about 450 man Sv between the first two five-year periods. It subsequently decreased in the third and fourth periods, to about 330 and 240 man Sv, notwithstanding a twofold increase in the energy generated over the same period. The normalized average annual collective effective dose per reactor initially rose from 5.5 to 7.0 man Sv over the first two periods, but dropped to 4.0 and then 2.7 man Sv in the last two periods. The corresponding values normal-ized to the energy generated, man Sv $(GW\ a)^{-1}$, were 18, 18, 7.9, and 4.8. Both parameters indicate significant reductions over the four five-year periods.

116. The average annual effective dose to monitored workers over the five-year periods has consistently fallen: 4.7, 4.5, 2.4, and 1.6 mSv. As with PWRs, there has been an almost threefold reduction overall. The worldwide average annual effective dose to measurably exposed workers, 2.7 mSv, is about 70% higher than that to monitored workers. The declining trend in doses is also seen in the values of NR_{15} and SR_{15}, with the fraction of the collective dose above 15 mSv having been 0.13 in 1990–1994.

117. There is considerable variation about the worldwide average values in both the trends and levels of dose in individual countries. However the differences do seem to be decreasing over time, and for the vast majority of countries reporting, a downward trend is apparent.

2. Heavy-water reactors

118. HWRs are used in several countries but most extensively in Canada, where the CANDU reactor was developed and has since been exported to a number of

countries. The main source of occupational exposure in these reactors is, in general, external irradiation, mainly from activation products in the coolant and coolant circuits. As in LWRs, most of the exposures arise during maintenance activities. Internal exposure, however, can also be a significant component of exposure, principally from intakes of tritium produced by activation of the heavy-water moderator.

119. The worldwide average number of HWRs increased from 12 in 1975–1979 to 31 in 1990–1994; the corresponding increase in the average annual energy generated worldwide was somewhat greater, from about 3 to 12 GWa. On average, 80% of this energy was generated by HWRs in Canada. The number of monitored workers in HWRs worldwide increased from about 7,000 to about 20,000 over the 20-year period, as shown in Figure IV. The average annual collective effective dose increased, from about 30 man Sv in the first five-year period to about 45 man Sv in the second period and 60 man Sv in the third; in the fourth period, however, it decreased significantly, to 20 man Sv. Internal exposure made a significant contribution to the overall dose; the contribution varied from year to year and between countries but on average was 30%, varying typically from 15% to 50%. Over the first three periods, the normalized average annual collective effective dose per reactor dropped slightly (2.6 to 2.3 man Sv), but the fourth period has seen a twofold reduction, to 1.1 man Sv per reactor. The corresponding values normalized to the energy generated, man Sv $(GW\ a)^{-1}$, were 11, 8.0, 6.2, and 3.0.

120. The average annual effective dose to monitored workers over the first two periods fell from 4.8 to 3.2 mSv but was then stagnant for the third period. However the last period, 1990–1994, saw a significant reduction, to 1.7 mSv, again a decrease by a factor of about 2. The data are dominated by the Canadian data and show a consistent downward trend. However there are significant variations around the worldwide averages, most notably for Argentina, where for the first three periods the average annual effective dose to monitored workers exceeded 10 mSv. For the latest period it fell to 8.2 mSv (compared with 1.1 mSv for Canada). These differences are also very apparent in the distribution ratios: in Argentina 65% of the collective dose comes from individual annual doses in excess of 15 mSv, while in Canada the corresponding figure is 11%.

3. Gas-cooled reactors

121. There are two main types of GCRs: Magnox reactors, including those with steel pressure vessels and those with prestressed concrete pressure vessels, and advanced gas-cooled reactors (AGRs). Another type, HTGRs, reported on previously [U6], is no longer in operation. Most of the experience with GCRs has been obtained in the United Kingdom, where they have been installed and operated for many years. Initially, the GCRs were of the Magnox type, but throughout the 1980s, the contribution of AGRs, both in terms of their installed capacity and energy generated, became more important. The relative importance of AGRs will increase as Magnox reactors are decommissioned.

122. The UNSCEAR 1993 Report [U3] investigated the differences between the Magnox reactors and AGRs. These arise mainly from the use of concrete (as opposed to steel) pressure vessels in the AGRs (and later Magnox reactors) and the increased shielding they provide against external radiation, the dominant source of occupational exposure. That Report identified significant differences between the various types, with the average annual effective dose in first-generation Magnox steel-pressure-vessel reactors remaining uniform at about 8 mSv whereas the values for Magnox concrete-pressure-vessel reactors and AGRs were less than 0.2 mSv. During the current reporting period, 1990–1994, significant dose reductions were effected in the Magnox reactors. The highest average annual effective doses, about 3.0 mSv, were at the Chapelcross reactors (the earliest of the designs). More detailed information can be found in the reviews of radiation exposures in the United Kingdom [H3, H9]. In this Annex no distinction has been made in Table 7 between the various types of GCRs.

123. The worldwide number of GCRs averaged over five-year periods has not differed by more than 10% from 40. The average number in operation during 1990–1994 was 38. The average annual energy generated increased over the four five-year periods from 5.4 GWa to 8.4 GWa in the most recent period. Over 90% of this energy was generated in the United Kingdom. The number of monitored workers increased overall from 13,000 to 30,000, as shown in Figure IV. The average annual collective effective dose dropped from 36 through 34 and 24 to 16 man Sv over the four periods. Over the 20 years, the normalized collective dose per reactor decreased, from 0.9 to 0.4, while the corresponding values for energy generation, man Sv $(GW\ a)^{-1}$, also decreased, from 6.6 to 2.0.

124. The average annual effective dose to monitored workers worldwide, averaged over five-year periods, fell progressively from 2.8 mSv in the first period by a factor of about 2 between each period, so that the value for 1990–1994 was 0.5 mSv. The fraction of the monitored workforce receiving annual doses in excess of 15 mSv has been small, decreasing from 0.02 by a factor of more than 100. Between 1992 and 1994 there was only one instance of a worker at a United Kingdom GCR exceeding 15 mSv in a year, and only 10 workers exceeded 10 mSv in a year [H9].

4. Light-water-cooled graphite-moderated reactors

125. LWGRs were developed in the former USSR and have only been installed in what is now the Russian Federation and Lithuania. No data for LWGRs were reported in the UNSCEAR Survey of Occupational Radiation Exposures, but data relating to the two countries have been obtained from ISOE and other sources [L5, R2]. Data on energy generation were taken from Annex C, "*Exposures to the public from man-made sources of radiation*".

126. Overall the number of LWGRs increased, from 12 in the first period to 20 during 1990–1994, and the corresponding average annual energy generation increased, from 4.4 to 9.4 GWa. The number of monitored workers increased over the first three periods, from about 5,000 to 13,000, but no data are available for 1990–1994. The average annual collective effective dose increased significantly over the periods, from 36 to 62 to 170 to 190 man Sv. This increase is also reflected in the normalized collective dose values; that per reactor rose from 3.0 to 9.4 man Sv and that for energy generation rose from 8.2 to 20.3 man Sv $(GW\ a)^{-1}$. The average annual effective dose to monitored workers is estimated to have risen from 6.6 mSv in the first period to 13 mSv in the third. No data are available for 1990–1994, but given that the collective dose rose relative to the preceding period it is likely that the exposure of monitored workers also increased. No data have been available on the fractions NR_{15} or SR_{15}, but the other data suggest that they must be significant.

127. It was suggested in the UNSCEAR 1993 Report [U3] that the large increase in collective dose between the second and third periods (62 to 170 man Sv) was artificial in that the data included a significant component from the after-effects of temporary work at Chernobyl. However the data for 1990–1994 show another increase in exposure. Also, the data from Lithuania tend to support the overall high levels of exposure.

5. Summary

128. Data on occupational exposure at reactors worldwide are summarized in Table 8. The worldwide number of power reactors averaged over the five-year periods increased from about 190 in the first period to 421 in 1990–1994. The corresponding increase in average annual energy generation was from 55 to 230 GWa. Averaged over the whole period about 85% of the total energy was generated in LWRs (of this about 70% was from PWRs and 30% from BWRs), with contributions of about 5% each from HWRs, GCRs, and LWGRs. The number of monitored workers increased from about 150,000 to 530,000. The period 1990–1994 is the first for which a reasonably robust estimate of measurably exposed workers, some 290,000, is available.

129. The annual collective effective dose averaged over five-year periods increased over the first three periods (600, 1,000, and 1,100 man Sv) but has fallen back to 900 man Sv for 1990–1994. The trends in annual values are shown in Figure V. About 80% of the collective dose occurred at LWRs, with broadly similar contributions from PWRs and BWRs despite the fact that they were more than twice as many PWRs as BWRs. Averaged over all the periods, the contribution from HWRs has been 5%, that from GCRs 3%, and that from LWGRs about 13%.

130. The normalized collective effective dose per reactor averaged over all reactors rose between the first two periods, from 3.2 to 3.6 man Sv, but dropped to 2.8 and then 2.1 man Sv over the last two periods. The corresponding figures per unit energy generated are 11, 10, 5.9, and 3.9 man Sv $(GW\ a)^{-1}$. A generally decreasing trend is apparent for both normalized figures for most reactor types. The exception is LWGRs, for which a roughly threefold increase was seen over the four periods.

131. The annual effective dose to monitored workers averaged over all reactors fell steadily, from 4.1 mSv to 1.4 mSv. For the 1990–1994 period, data were available to enable an estimate of the annual effective dose to measurably exposed workers of 2.7 mSv. This downward trend in annual dose to monitored workers is evident for each reactor type except LWGRs, although there are some differences between reactor types in the magnitudes of the doses and in their rates of decline.

132. Data on the distribution ratios NR_{15} and SR_{15} are less complete than data for other quantities, but for 1990–1994 more dose profile information is available for dose bands up to 1, 5, and 10 mSv. Values of NR_{15} and SR_{15} averaged over all reported data are given in Table 8. They show the fraction of monitored workers receiving doses in excess of 15 mSv to be about 0.08 in the first period, decreasing to <0.01 in 1990–1994. The corresponding fraction of the collective dose arising from doses in excess of 15 mSv decreased from 0.60 to 0.08.

E. FUEL REPROCESSING

133. Commercial-scale reprocessing of irradiated spent fuel from nuclear power facilities to recover uranium and plutonium is performed in only two countries, France and the United Kingdom. Smaller facilities are in operation in Japan, India, and the Netherlands (experimental facility), and the Russian Federation has been reprocessing fuel for reactors developed in that country. Although the process varies depending on the nature of the fuel reprocessed, it generally involves the dissolution of the spent fuel elements in an acid bath, followed by the chemical separation of uranium and plutonium from the fission products and other actinides produced in the fuel. In spite of the fact that most fuel elements are cooled for up to several years before being reprocessed, they still contain high levels of radioactive materials at the time of reprocessing, and remote operations and heavy shielding are necessary for the adequate protection of workers.

134. Data on occupational exposure in reprocessing plants are summarized in Table 10. The UNSCEAR 1993 Report [U3] analysed the differences between plants reprocessing metal fuel and oxide fuel. The UNSCEAR Survey of Occupational Radiation Exposures for 1990–1994 made no such differentiation. The numbers of plants involved in reprocessing worldwide is limited, with the largest contributions during 1990–1994 coming from France, the Russian Federation, and the United Kingdom. While worldwide estimates have been derived, there are some significant differences between the data set for 1990–1994 and the sets for previous periods, and any comparisons

with previous worldwide estimates should be drawn with extreme caution. In the earlier periods the worldwide estimates of average annual collective effective dose were dominated by the contribution from the United Kingdom (65% over all three periods) and, to a lesser extent, by France (22%) and United States (13%). For 1990–1994, the Russian contribution of 33.9 man Sv accounted for over 50% of the worldwide average annual collective effective dose. As might be expected, this large contribution significantly increased the worldwide estimate, some 67 man Sv, in contrast to the three previous periods, during which the worldwide average annual dose declined, from 53 to 47 to 36 man Sv. If the Russian data had been excluded, the downward trend would have been maintained.

135. Given the confounding impact of the Russian data, it is perhaps more instructive to look at trends in the individual countries. The number of monitored workers in France, Japan, and the United Kingdom all increased by about 30% relative to the preceding period and by a factor of between 2 and 4 relative to 1975–1979. In the United Kingdom, the average annual collective effective doses over the four five-year periods steadily reduced: 47, 40, 29 and 21 man Sv. The corresponding figures for France were about 13 man Sv in each of the first three periods but only 4.7 man Sv for 1990–1994. The data for the smaller reprocessing operations in Japan rose over the first three periods, from 0.38 to 1.8 man Sv, and then decreased, to 0.82 man Sv. The data for the United States relate to Department of Energy facilities [D4], which are mainly associated with defence activities, but as was done for earlier UNSCEAR reports, they have been included under reprocessing. The apparent rise in the number of monitored workers in the United States is likely to be related to changes in monitoring practices rather than to any increase in the activity. (This matter is addressed more fully in Chapter VI, Defence Activities). Compared with the previous period, the average annual collective effective dose in 1990–1994 decreased by a factor of about 3, from 4.9 to 1.6 man Sv; a similar reduction from 2.7 mSv to 0.82 mSv is seen in the values for doses to measurably exposed workers.

136. The average annual effective dose to monitored workers fell consistently over the four periods for both France, from 2.9 to 0.36 mSv, and the United Kingdom, from 8.3 to 2.0 mSv. The Japanese data follow the pattern for collective dose, with a rise over the first three periods from 0.44 to 0.98 mSv and a drop to 0.32 mSv for 1990–1994.

F. WASTE MANAGEMENT

137. The volume of radioactive waste from the nuclear fuel cycle (and also from medical and industrial uses) is increasing, with very little having been moved thus far to final waste repositories. Consequently, doses associated with waste management are of increasing importance. However, in the dose data currently available, the data specifically associated with waste management are rarely identified separately. This is a matter that needs to be addressed in future reviews, which could include an indication of the general magnitude of the practice and the present exposures to workers involved.

138. While no data are readily available on exposures, there are some data on the magnitude of the practice in relation to the nuclear fuel cycle. A review by IAEA [I21] of the nuclear fuel cycle and waste management gives an overview for 1993 that can be considered typical for the period. At that time there were 301 research and test reactors in operation, 14 under construction, and 260 shut down. Of the total, 90 that were in operation, 6 that were under construction, and 9 that were shut down were in developing countries. Most of the reactors had been built 25–30 years earlier, when it was assumed that the irradiated fuel would eventually be shipped back to the country of origin. This has frequently not been possible. In some countries, highly enriched, high-burn-up fuel is stored in facilities that were not designed for such long-term storage. While the management of spent fuel from research reactors poses its own problems, the overall spent fuel problem is dominated by fuel from power reactors. There are a number of strategies for dealing with spent fuel: some is stored at the reactors, some at centralized facilities away from the reactor, and some is reprocessed, generating high-activity waste. Finding a permanent repository for active waste has so far proved to be an intractable problem in the vast majority of countries, and a number of interim storage facilities have been developed, based on either wet storage in ponds or dry storage facilities.

139. In 1993 the spent fuel arising from all types of reactors was about 10,000 t HM (heavy metal), giving an estimated cumulative total of over 145,000 t HM. About 95,000 t HM was being stored in 1993, which was over 20 times the annual reprocessing capacity at that time. The storage capacity at reactors was estimated to be about 59,000 t HM, 94% of it wet storage and 6% dry storage. To date, the doses associated with the management of spent fuel have been subsumed into data for reactor operation, reprocessing, and research, with different countries taking different approaches. The growing computerization of dose records and the advent of active personal dosimeters could make it possible to segregate dose data and allow doses associated with waste management to be separately identified.

140. Although the management of spent nuclear fuel is a major source of exposure from nuclear waste, there are others, notably the management of waste industrial and medical sources and the decommissioning of nuclear facilities. The latter will lead to a growing proportion of the waste managed, and data will be needed for doses arising in decommissioning to carry out a comprehensive assessment of the doses from waste management.

G. RESEARCH IN THE NUCLEAR FUEL CYCLE

141. It is difficult to estimate the levels of occupational exposure that can unequivocally be attributed to research and development in the commercial nuclear fuel cycle. Few data are reported separately in this category, and even when they are, uncertainties remain as to their proper interpretation. The main difficulties of interpretation are as follows:

(a) data are often compiled for research establishments whose main, but not sole, function is to undertake research and development associated with the commercial nuclear fuel cycle. The fraction devoted to this function is rarely given;
(b) some fraction of the occupational exposures attributed in the preceding Sections to particular parts of the fuel cycle contains a contribution from research and development, but the magnitude of this fraction is difficult to estimate;
(c) collective doses from research have been normalized in terms of the nuclear energy generated in the year in which the research was performed. While this convention has the benefit of simplicity, practicability, and convenience, the validity of utilizing current levels of collective dose and energy generation is open to criticism. The benefits of research inherently accrue over a period quite different from that in which the research was performed, and the normalization should in fact take account of the total energy generated in the period in which the benefits are deemed to accrue. In a rapidly developing industry, it is evident that normalization based on current energy generation is likely to lead to a large overestimate in the early years, followed by an underestimate later, as the industry matures and the amount of research declines.

142. Occupational exposures arising in nuclear research, averaged over five-year periods, are summarized in Table 11. There is considerable variation in the levels of collective dose associated with research activities in each country, reflecting, among other things, the relative role of nuclear energy in the national energy supply and the extent to which nuclear technology was developed domestically or imported. The reported annual collective effective doses range from a very small fraction of a man sievert (e.g. in Finland) to about 38 man Sv in the United Kingdom for the earliest period. Country-to-country differences are to be expected in the occupational exposures associated with this category; however, these differences may have been exaggerated significantly by different reporting approaches. The collective effective dose attributed to research in the three previous periods has been dominated by the contributions from the United States and the United Kingdom. Each has shown a steady downward trend, from 33 to 19 man Sv and from 38 to 24 man Sv, respectively, over the first three periods. For 1990–1994, the contribution from the United Kingdom fell dramatically, to 5.6 man Sv. This and the halving of the number of monitored workers reflects both better protection standards and a large reduction in the United Kingdom's nuclear research programme. Comparable data are not available from the United States. The largest contribution in the 1990–1994 period came from the Russian Federation, which reported an average annual collective effective dose of about 16 man Sv (over the years 1992–1994). This is the first period for which data have been available. The only other countries reporting annual doses of 1 man Sv or greater are Canada, France, India, and Japan; each of which has a significant nuclear research and development programme. In each case, while the extent decrease varies, there has been a downward trend in collective dose.

143. Worldwide levels of occupational exposure associated with research are also given in Table 11. They were estimated from the reported data, with extrapolation based on GDP. This method was adopted in preference to the extrapolation used for other parts of the nuclear fuel cycle, which were based on fuel fabricated, energy generated, etc.; the difficulties, identified previously, of using energy generation as a basis for normalizing research were responsible for the change to GDP. The GDPs of the countries reporting data represented about 40% of the worldwide total. On average, therefore, the reported data have been scaled upwards by a factor of about 2.5; there is, however, considerable variation about this average for particular regions.

144. The annual number of monitored workers in research worldwide, averaged over five-year periods, has remained remarkably constant at between 120,000 and 130,000. The average annual worldwide collective effective dose dropped from 170 to 100 man Sv over the first three periods and was slightly lower, 90 man Sv, for 1990–1994. This profile is mirrored in the worldwide estimates for the annual effective dose to monitored workers, which fell from 1.4 to 0.82 mSv over the first three periods and decreased marginally to 0.78 mSv for 1990–1994. There is a similar profile for the fraction of the monitored workforce exceeding 15 mSv, which dropped from about 0.04 to <0.01. The corresponding figures for the fraction of the collective effective dose arising from annual doses in excess of 15 mSv has shown a more steady reduction, with values of 0.42, 0.39, 0.30, and 0.22. It should be noted that there are some considerable variations between countries and that for 1990–1994 no dose distribution data were available for the largest contributor to the collective dose, the Russian Federation. For the first time, reasonable data were available on doses to measurably exposed workers, and the average value worldwide was estimated to be 2.5 mSv; greater by a factor of 3 than the average annual dose to monitored workers.

145. Some of the problems of making meaningful estimates of the normalized collective dose (relative to energy generated) were identified in paragraph 141. They involve how to deal with the different temporal distributions of the benefits and costs of research. This was discussed in some detail in the UNSCEAR 1993 Report [U3], where it was concluded that for the purpose of assessing overall values of normalized collective doses for the whole fuel cycle, a value of 1 man Sv $(GW\ a)^{-1}$ could be assumed to be generally applicable for research, irrespective of when it was undertaken. The con-tinued applicability of this approach has been reviewed and confirmed.

H. SUMMARY

146. Trends in worldwide occupational exposures from each stage of the commercial nuclear fuel cycle are summarized in Table 12 and illustrated in Figures VI and VII. The data are annual averages over five-year periods. During the first three periods, the number of monitored workers in the commercial fuel cycle rose, from about 560,000 to 880,000, but in 1990–1994 the number fell to 800,000 (Figure VI). This was largely due to a three- to fourfold reduction in the estimated number in the mining sector, from 260,000 to 69,000. The latter figure may be an underestimate attributable to the limitations of the data set, but all the other indicators support a significant reduction in this component of the monitored workforce. In the first five-year period mining accounted for over 40% of the workforce, but over the four periods reactor operation has become the dominant component of the monitored workers and at 530,000 now accounts for about 65% of the total.

147. The average collective effective dose, averaged over five-year periods, initially increased from 2,300 to 3,000 man Sv but in the last two periods decreased to 2,500 and then 1,400 man Sv (Figure VII). This almost twofold decrease between the last two periods is again dominated by a reduction by a factor of 3 to 4 in the collective dose from mining. The same cautions noted in the preceding paragraph apply here, but the supporting evidence of a general reduction in collective dose over all the countries and the cessation of underground mining in a number of countries make it more likely that the values are not significant underestimates.

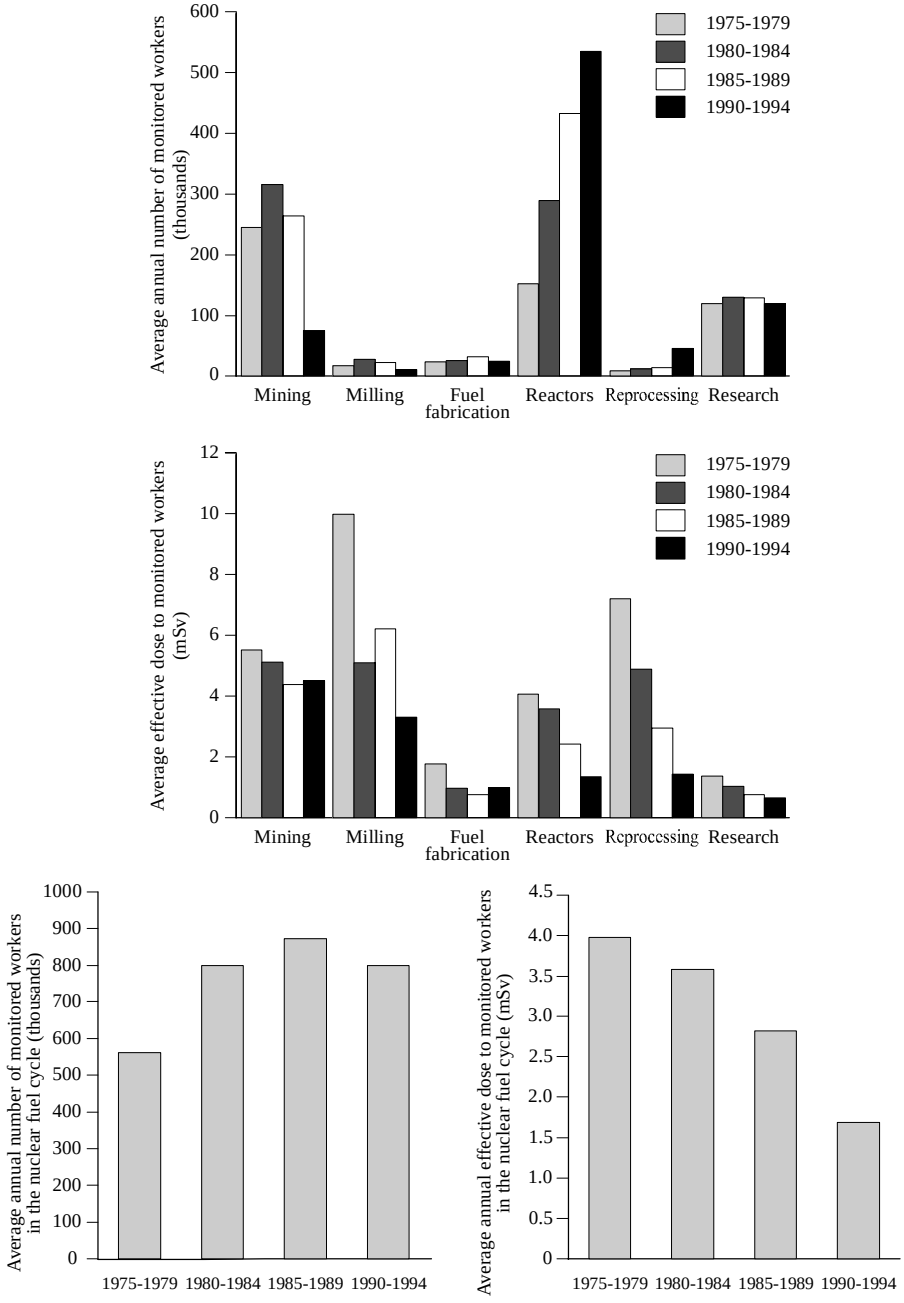

Figure VI. Trends in numbers of monitored workers and doses to workers in the nuclear fuel cycle.

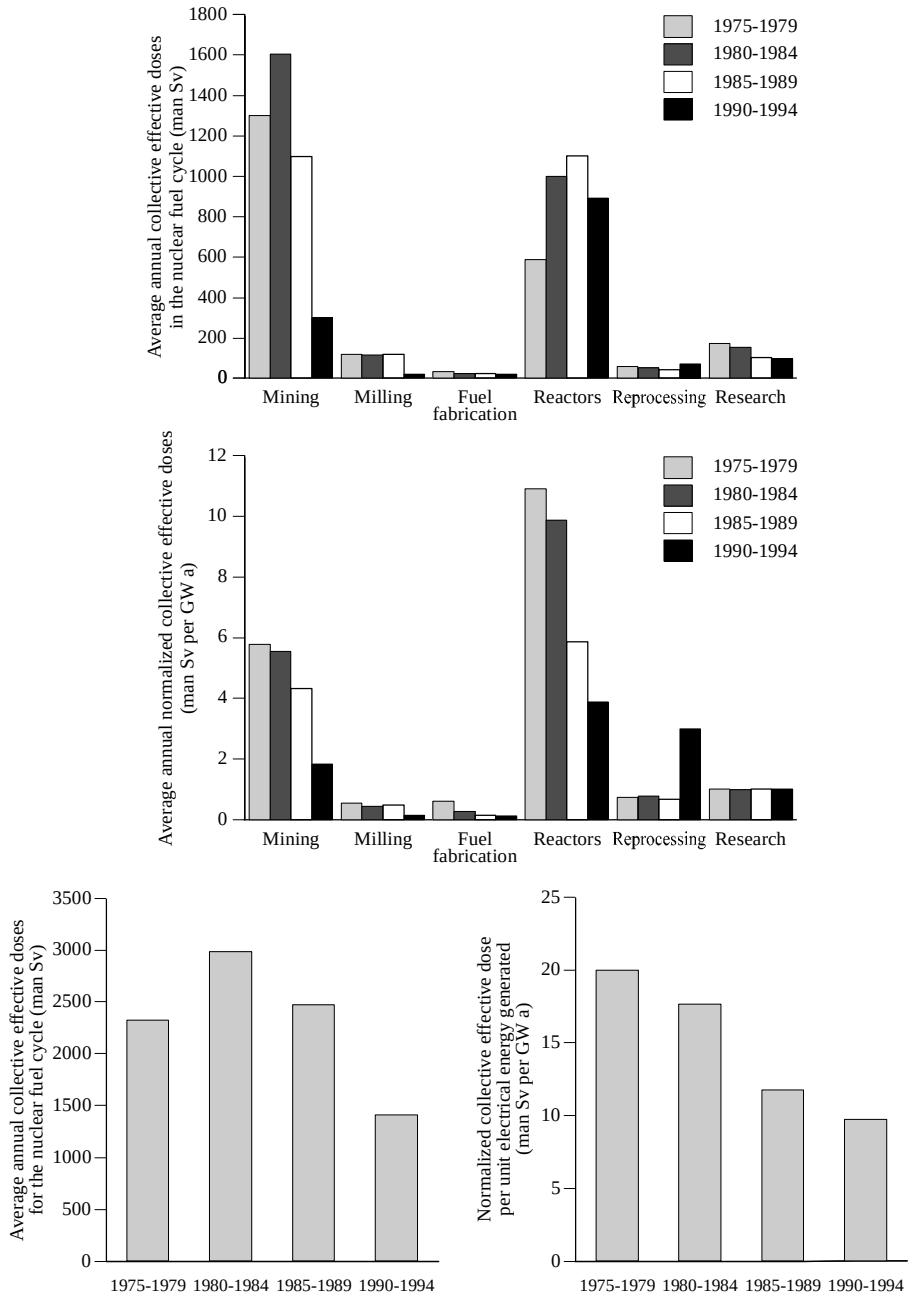

Figure VII. Trends in collective doses and normalized collective doses in the nuclear fuel cycle.

148. The average annual effective dose to monitored workers in the fuel cycle has decreased progressively, from 4.1 mSv in 1975–1989 through 3.7 and 2.9 mSv to 1.8 mSv in 1990–1994. There is considerable variation about these averages for the different stages of the fuel cycle. However, apart from the mining stage of the nuclear fuel cycle; where doses have been generally static at about 5.0 mSv, the overall downward trend is evident in all the other stages of the nuclear fuel cycle. For 1990–1994, there is for the first time a reasonably robust estimate of the average annual effective dose to measurably exposed workers. The estimated value of 3.1 mSv represents an increase in the value for monitored workers by a factor of just under 2. This factor varies considerably between the stages of the nuclear fuel cycle. The fraction averaged over five-year periods of monitored workers receiving annual doses in excess of 15 mSv (NR_{15}) has decreased from about 0.20 to about 0.01; the corresponding decrease in the fraction of the collective effective dose (SR_{15}) has been from about 0.63 to about 0.11. In the light of these reductions it has become relevant to look at the dose profiles in more detail. Accordingly, in the 1990–1994 UNSCEAR Survey of Occupational Radiation Exposures, additional data were sought for the ratios relevant to 10, 5, and 1 mSv. This effort is far from complete, but it provides a reasonable dose profile within the various stages of the nuclear fuel cycle that will serve as a baseline for future reviews.

149. The normalized collective effective doses for each stage of the fuel cycle are shown in Figure VII. The collective dose from mining, milling, fuel fabrication, and fuel reprocessing have been normalized to the energy equivalent of uranium mined or milled or to the fuel fabricated or reprocessed in the respective periods. For research associated with the fuel cycle, 1 man Sv $(GW\ a)^{-1}$

has been assumed in each period. The overall normalized collective effective dose (i.e. averaging over all stages in all fuel cycles and taking account of their relative magnitudes) is estimated to be (in chronological order) 20, 18, 12, and 9.8 man Sv (GW a)$^{-1}$ for the four periods. This again shows an overall downward trend.

III. MEDICAL USES OF RADIATION

150. Radiation is used in medicine for both diagnostic and therapeutic purposes. The physicians, technicians, nurses, and others involved constitute the largest group of workers occupationally exposed to man-made sources of radiation. The wide range of applications and the types of procedures or techniques employed in the context of patient exposure are reviewed in Annex D, "*Medical radiation exposures*", where changes in practice and possible future trends are also discussed. Consideration is limited here to the occupational exposures that arise from the application of these procedures. Data on occupational exposures are presented for workers in each of the following areas: diagnostic radiology, dental radiology, nuclear medicine (diagnostic and therapeutic), radiotherapy, other medical practices, and all medical uses of radiation grouped together.

151. Previous Chapters of this Annex contained cautionary remarks about the accuracy or validity of reported statistics on occupational exposures and the extent to which they can be fairly compared, either between countries for the same occupational group or between occupational groups in the same or different countries. It is in the area of medical uses of radiation where these cautionary remarks are most important, and great care must be exercised in interpreting and evaluating the various statistics. In the medical field, an important difference is where the dosimeters are located (in particular, whether they are above or below lead aprons when these are worn). Two more factors complicate matters: firstly, the radiation that contributes most to the overall occupational exposures from the medical uses of radiation is non-uniform and of low energy and, secondly, the approach used to derive effective doses from dosimeter measurements can have important implications for the comparability of occupational exposures.

152. Some of the above differences can been seen in Table 2 and in the notes to the various tables covering medical uses. However the information is patchy, and it has proven impracticable in this analysis to revise or normalize the reported exposures to ensure that they can be fairly compared. Accordingly, when worldwide levels of exposure were estimated from the available data, no distinction was made between doses measured, recorded, or reported in different ways; all reported doses were assumed to be adequate surrogates for effective dose. More attention needs to be given to this matter to afford better comparability between doses arising in different circumstances and to enable more reliable estimates of worldwide levels of occupational exposure.

153. National data for the various categories of medical uses of radiation averaged, where possible, over five-year periods, are given in Table 13. It should be noted that some countries do not keep data divided into the various medical use areas, so their reported data appear in the "all other medical uses" part of Table 13. To provide a more secure basis for estimating worldwide exposures, all the data provided on medical uses have been aggregated by country (Table 14). The reported data have also been aggregated by region (Table 15).

154. Worldwide levels of exposure have been estimated from the national data by extrapolation within particular regions based on GDP, as described in Section I.E. In general the collective dose for each practice correlated well with GDP, but there were exceptions for some countries. The degree of extrapolation needed varied with medical use and, more importantly, by region. The vast majority of extrapolations were by a factor of from 1.5 to 5. However, for eastern Europe and the remainder regions, the factor was typically 20, in the first case mainly because there were no data from the former USSR, and in the second because so few countries provided data. Nevertheless the regional estimates are consistent with those for previous periods.

155. Summaries of the worldwide exposures, by practice and by region, are given in Tables 16 and 17, respectively. Formally, the United States was treated as a separate region and the rest of the OECD as another region. In this Annex the main confounding factor in deriving the worldwide exposure estimates has been the absence of data for the United States. As was noted in Section I.E, the Committee has developed an approach for estimating collective dose where no regional data are available. In essence this estimates the regional dose by prorating the sum of the GDPs for the total collective dose reported. This approach generally worked well, but it produces figures for the United States that are significantly lower than for previous reporting periods and therefore calls into question the appropriateness of the normal method of estimation.

156. The Committee has considered alternative methods of estimating the values for the United States. The region most similar to the United States in this respect is the rest of the OECD. Earlier UNSCEAR reports derived for each region the collective effective dose per unit GDP (man Sv per 10^{12} United States dollars). While there have been clear differences in these values for the two regions, the values have been converging. For the last three five-year periods, the ratios of this parameter for the United States to that for the rest of the OECD have been 3.4, 2.8, and 2.4 in chronological order. It would therefore be reasonable to presume that the convergence has continued and that a ratio of approximately 2.0 would be appropriate for

1990–1994. The ratio of the GDPs for the two regions is approximately the inverse of this, namely 0.5. On this basis the values for the United States approximate to those for the rest of the OECD. World estimates using this approach are included in Tables 13, 14, 16, and 17. The resulting values for the United States are consistent with the trends of increase in number of monitored workers and decrease in annual collective effective dose observed over the first three periods. Similar consistent trends are found in the world estimates calculated by this method. For comparison, world estimates based on the method described in Section I.E are given in brackets in the tables.

A. DIAGNOSTIC RADIOLOGY

157. It is noted in Annex D, "*Medical radiation exposures*" that during the last 20 years, medical imaging has undergone a technological revolution; steady advances in the quality of x-ray images and in patient protection have ensured a continuing role for diagnostic x-ray use in health care, although alternative modalities for diagnosis, such as ultrasound and, particularly in developed countries, magnetic resonance imaging (MRI), are becoming increasingly available. Nevertheless, x-ray examinations remain the most frequent use of ionizing radiation in medicine. Occupational exposure in medicine depends on a number of factors, the most important of which is the x-ray procedure. There are three general procedures that constitute sources of exposure: radiography, fluoroscopy, and special examinations. Radiography here is taken to include general-purpose radiography, computed tomography, and mammography. Special examinations are taken to include cardiac catheterization, angiography, and interventional procedures.

158. Workload is an important factor; in general, occupational exposures are directly proportional to the workload [N3]. Training and the use of protective aprons are relevant, particularly in the control of exposures during fluoroscopy and special examinations.

159. Radiography is by far the most widely used x-ray imaging technique. During radiography with fixed installations, the radiographer would normally be expected to stand in a control booth that is typically shielded as a secondary barrier against x-ray tube leakage and scattered radiation from the room and patient. Depending on room size and barrier thickness, the dose to a radiographer in the control booth area is typically less than 1 μSv for a single film taken with a technique of 80 kVp and 40 mA s [N3]. Mobile units, however, operate in an unshielded environment and are therefore of greater concern.

160. Although doses to patients from computed tomography (CT) may be high, the exposure of staff is usually low, because the primary x-ray beam is highly collimated, and scattered radiation levels are low. In all such CT units, leakage of radiation has been reduced to near zero. For staff in the control room of a properly designed facility, computed tomography does not represent a significant source of exposure. Only if an individual is required to remain in the room with the patient during examination can a measurable exposure be expected.

161. Fluoroscopic procedures, including those of a special nature, constitute fewer than 10% of all examinations in the United States [N2] but are by far the largest source of occupational exposure in medicine. During fluoroscopy, the x-ray tube may be energized for considerable periods of time. Fluoroscopic procedures require the operator to be present in the examination room, usually close to the patient. In fact, the patient is the main source of exposure because of scattered radiation.

162. In special examinations, fluoroscopic times may be long and the accompanying radiographic exposures can be numerous. Staff are nearly always present in the room close to the patient, and it is difficult to shield against scattered radiation. Staff exposure rates associated with the examinations in such rooms can be 2 mGy h^{-1} or more, depending on location and fluoroscopic technique. Cardiac catheterization, in particular, can constitute a source of relatively high exposure. Procedures involve not only radiography and fluoroscopy, some also require cineradiography. During cineradiography, the table-top air kerma rate may vary from 0.2 to 1 Gy min^{-1}. Although an examination may require only 30–40 seconds of cinegraphic time, total exposures to staff can be high [N3].

163. Data on occupational doses from diagnostic radiology from the UNSCEAR Survey of Occupational Radiation Exposures are given in the first part of Table 13 and Figure VIII. The reported number of monitored workers for the 1990–1994 data set is about two thirds of the number for the previous five-year period, but from a wider range of countries. The countries reporting data on occupational exposures from diagnostic radiology accounted for about 20% of the GDP worldwide. This compares with 18% for the countries reporting data for the preceding five-year period [U3].

164. The last three periods have shown an increasing trend in the annual number of monitored workers involved worldwide in diagnostic radiology. However, the estimate for the present period, 950,000 (compared with 1.4 million for 1985–1989), appears to indicate a reversal of this trend. Similarly, the estimated annual average collective dose is significantly reduced: 470 man Sv compared with 760 man Sv for the preceding period. These comparisons should be regarded with caution, because unlike in earlier years, the questionnaire completed by countries included a category "all other medical uses". Some countries were only able to provide data covering all medical uses aggregated together, and they reported them under "all other medical uses". If the worldwide estimates deriving from the "all other medical uses" category were to be distributed among the named medical practices in proportion to the world estimates for these practices, then the worldwide estimates for diagnostic radiology for 1990–1994 would increase to 1.3 million monitored

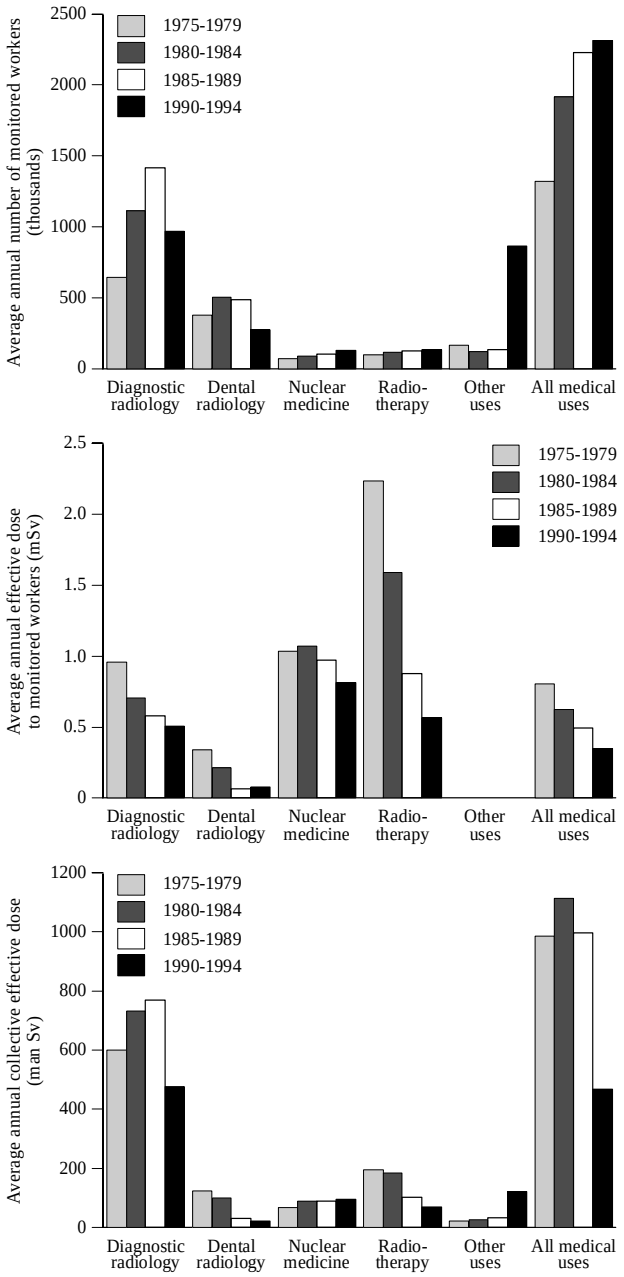

Figure VII. Trends in number of monitored workers, doses to workers and collective doses for medical uses of radiation.

workers with an annual collective effective dose of 540 man Sv. These figures are more in line with those from 1985–1989 but still show a downward trend. This could be explained by a possible move in OECD countries (which dominate the data) to cut back on the monitoring of staff in response to economic pressures and also by the impact of efforts to improve radiological protection practices.

165. The average annual effective dose to monitored workers averaged over the four five-year periods has fallen from 0.94, through 0.68 and 0.56 to 0.50 mSv for 1990–1994. This same downward trend is evident in the data for most countries and regional groupings, but there is considerable variation between countries in the level of dose and the extent of the decrease. Most average annual doses are below 1.0 mSv, but somewhat higher values are reported for Pakistan, Peru, the Syrian Arab Republic, and the United Republic of Tanzania. The data set for 1990–1994 contained more data on the numbers of measurably exposed workers and the doses they received. This has enabled a more robust worldwide estimate of this parameter: 1.3 mSv; it is higher by a factor of 2.7 than that for monitored workers.

166. Some data from the United Kingdom, given in Table 18, show the breakdown of exposures by occupational grouping for some diagnostic radiology departments [H3]. It can be misleading to compare the calculated averages for groups because of the large number of low doses, but some conclusions can be drawn on the basis of these data. Radiographers receive less than 0.1 mSv in a year, whereas radiologists receive a few times more. Cardiologists tend to be the most exposed; their average annual dose was 0.4 mSv, and an appreciable proportion received more than 1 mSv.

167. Tables 19 and 20 show the distribution of doses for the medical sector in Spain [H8] and France, respectively [C3]. The Spanish data also show the distribution for 1989 and include other use sectors. In 1989 in Spain the number of medical sector workers exceeding 20 mSv (90) was greater than the number in the nuclear fuel cycle sector. By 1995 there had been a significant drop in this number (to 22) and in the collective dose and the average individual dose. The higher doses are in diagnostic radiography and particularly in interventional radiology. This picture is also reflected in Table 20, which gives the French data for 1995. According to these data, 31 persons in diagnostic radiology exceeded the value of 50 mSv in that year. Worldwide there have been a number of instances of deterministic skin effects arising from long fluoroscopic exposures [F2, W5].

168. Regional variations in the data for each medical sector are given in Table 15. For diagnostic radiography, the regional average individual annual dose is generally 0.3–0.4 mSv; however, average doses greater than 1 mSv are derived for east Asia, Latin America, and the remainder region.

B. DENTAL PRACTICE

169. In almost every dental office or clinic, a diagnostic x-ray machine is available and frequently used. The number of x-ray devices used in dentistry is thus extremely large. For example, in France in 1993 more than 35,000 devices were estimated to be installed [V1]. Occupational exposure in dentistry is from scattered radiation from the patient and leakage from the tube head, although the latter should be insignificant with modern equipment. The general trend over the last 30 or more years has been a dramatic increase in the number of personnel involved in dental radiology but a steady decrease in the collective dose [N3]. A majority of dental practitioners do not receive measurable doses, and indeed some regulatory authorities do not require routine individual monitoring except where the workload is high.

170. The sum of the GDPs for those countries reporting data was about 50% of the worldwide total in the first five-year period, increasing to 60% in the third. For 1990–1994, this share decreased to 40%, largely due to the absence of data from the United States. On average, therefore, the data have been scaled up by a factor of 2.5 but with considerable variation about this average value for particular regions. However, it has to be noted that the United States data in previous periods dominated world estimates out of proportion to the country's GDP. For example, in 1985–1989 the United States data accounted for 64% of the worldwide estimates of monitored workforce and 74% of the annual collective effective dose. Therefore, while worldwide estimates have been made for 1990–1994, it may be instructive to also compare the worldwide estimates with the United States data subtracted.

171. The estimates of the worldwide average annual number of monitored workers (Table 13) for the preceding three five-year periods were 370,000, 500,000, and 480,000, so that the estimate of 265,000 for 1990–1994 appears to depart from these figures. If the data for the United States are removed, then the figures, in chronological order, are 155,000, 241,000, 173,000, and 147,000. This suggests broad comparability over the four periods and, perhaps, the sensitivity of the estimation methods to the profile of the data sets.

172. The average annual collective dose was about 120 man Sv in the first period, decreasing to about 25 man Sv in the third, with most of the decrease having occurred between the second and third periods. The corresponding estimate for 1990–1994 is 16 man Sv, continuing the downward trend. The earlier periods were dominated by United States data, but if these are subtracted, the values for the four periods are 40, 30, 13, and 10 man Sv, still a downward trend. It would be reasonable to expect the United States to continue to show a downward trend. Therefore the worldwide estimate for annual collective effective dose of 16 man Sv is considered more robust than the estimate of the number of monitored workers. It can be stated with some confidence that dental radiology does not contribute significantly to medical occupational exposures.

173. The annual effective dose to monitored workers worldwide averaged over five-year periods fell progressively, from 0.32 mSv in the first period to 0.05 mSv in the third. The estimate for the fourth period, 0.06 mSv, is a marginal increase but well within statistical uncertainty and in any case a low value. The regional values are within a factor of 5 of the overall average but still low. However there is considerable variation for some countries.

174. During 1990–1994 more data were reported for measurably exposed workers and dose distributions. The value of 0.28 for SR_{15} is approximately twice that for the preceding period. High individual doses in dentistry are not unknown; however, it is probable that the recorded doses reflect not the actual exposure of individuals but the fact that personal dosimeters are once in a while left in areas where they could be irradiated. Given the relatively low collective dose and average individual doses, it would not take many such instances to distort the collective dose distribution.

C. NUCLEAR MEDICINE

175. Whereas the broad aim in diagnostic radiology is the imaging of anatomy, that in nuclear medicine is more the investigation of physiological processes, with most procedures involving some form of measurement to quantify organ function. The use of radionuclide generators, particularly ^{99m}Tc generators, requires handling tens of gigabecquerels of radioactive material during the elution process. The magnitude of the exposures when performing clinical nuclear medicine procedures depends on the precautions taken, including the use of syringe shields when performing the injections. Personnel must be close to the patient when giving the injections and while positioning the patient and camera. Usually, the imaging process makes the greatest contribution to the exposure of staff [B1]. Internal exposures of personnel are usually much less than external exposures; they are controlled by monitoring work surfaces and airborne concentrations, although some medical centres conduct routine bioassays [N3].

176. The total number of nuclear medicine procedures performed in the United States at the start of the 1990s was about 100 million; some 90% of these were radioimmunoassay investigations, and the remainder were *in vivo* administrations of radioactive materials. The number of *in vivo* nuclear medicine procedures increased by about 16%, from 6.4 million to 7.4 million per year from 1980 to 1990. This was less than the projected 8% per year increase expected over that period, because some techniques, such as the use of ^{99m}Tc for brain scintigraphy and ^{99m}Tc sulphur colloid liver imaging virtually disappeared. (Computed tomography and magnetic resonance imaging have largely replaced those techniques.) Some other techniques, such as positron emission tomography for mapping certain functions of the brain, show increasing use [N3]. The number of installations in France approved to undertake nuclear medicine in 1993 was 257 for *in vivo* therapeutic or diagnostic uses of radionuclides and 202 for *in vitro* uses [V1].

177. Radionuclides used for organ imaging, for example ^{99m}Tc, emit penetrating gamma radiation and give rise to the exposure of nuclear medicine staff and other persons in the vicinity of patients undergoing diagnosis or treatment. The dose rate at 1 m from a typical diagnostic patient is about 10 $\mu Sv\ h^{-1}$ after the administration of 0.74 GBq of ^{99m}Tc. Therapeutic administrations, for example 3.7 GBq of ^{131}I, give rise to a dose rate of about 200 $\mu Sv\ h^{-1}$ at 1 m from the patient, who will normally need to be segregated to reduce the exposure of other persons in the vicinity. Samples of blood taken from a patient also represent a source of staff exposure. Work involving the preparation and assay of radiopharmaceuticals tends to be associated with the highest occupational exposures in this field and

can give rise to annual doses up to about 5 mSv. Doses to hands and fingers can range up to the annual limit of 500 mSv, and various shielding devices can be used to reduce extremity doses. However, the majority of workers in nuclear medicine departments who are not directly handling radiopharmaceuticals receive very low exposures, typically less than 1 mSv in a year [N5].

178. Since the data on occupational exposure arising in nuclear medicine rarely distinguish between diagnostic and therapeutic applications, the present analysis is directed to overall levels of exposure in the field. Consideration is limited here to effective dose, to which extremity doses do not contribute. However in view of the potential for significant extremity doses in nuclear medicine, these would merit attention in any future analysis.

179. The sum of the GDPs for those countries reporting data accounted for about 12% of the worldwide total in the first period, rising to 18% for the third. The proportion for the present analysis was 19%, and allowing for regional reporting differences, on average the reported data have been scaled up by a factor of 7 but with considerable variation about this average value for particular regions and periods.

180. The annual number of monitored workers, averaged over the five-year periods, in nuclear medicine worldwide have steadily increased, with 61,000, 81,000, 90,000, and 115,000 being the estimated values for the four periods (see Tables 13 and 16). The corresponding values for the average annual worldwide collective effective dose are 62, 85, 85, and 90 man Sv. The annual effective dose to monitored workers worldwide, averaged over five-year period, varied little over the first three periods, with a typical value of 1.0 mSv. However, the estimated value for 1990–1994 was lower, 0.79 mSv. There were some regional variations, most notably for the Indian subcontinent and Latin America, which had values of about 2.3 mSv. Similarly, there are national variations, in particular for Pakistan and Peru, where somewhat higher doses were experienced. The worldwide average annual dose for measurably exposed workers during 1990–1994 was 1.4 mSv, with the values for the Indian subcontinent and Latin American being about 4.0 mSv.

181. The fraction of the monitored workforce worldwide receiving annual doses in excess of 15 mSv continues to be small. Indeed, only some 2% exceeded 5 mSv. This is the situation in most countries, but there are exceptions; in particular Pakistan (26% in excess of 15 mSv) and Cuba (13% in excess of 10 mSv). These variations are also evident in the distribution ratios for collective dose.

D. RADIOTHERAPY

182. Therapeutic uses of ionizing radiation are quite different in purpose from diagnostic radiological procedures. Radiotherapy is an important treatment modality for malignant disease (see Annex D, "*Medical radiation exposures*"). There are three main categories of activity in radiation oncology: brachytherapy, external beam treatment, and therapy simulation [N3]. Brachytherapy, where there is manual loading of the radioactive sources, is usually the most significant source of personnel exposure. Exposures may occur during receipt and preparation of the sources, during loading and unloading, and during treatment. Personnel should not normally be present in the treatment room when external beam therapy is being used, with the possible exception of low-energy (50 kVp and less) x-ray contact therapy units, which are sometimes used for intracavitary treatments. Some exposures can, however, occur from ^{60}Co teletherapy units as a result of leakage while the source is in the off position and from radiation that penetrates the barrier during use. The types of exposure from linear accelerators, betatrons, and microtrons depend on the type of beam (photon or electron) and the beam energy. Below 10 MeV, exposure comes only from radiation that penetrates the protective barrier. Above 10 MeV, photonuclear reactions can produce neutrons and activation products. The neutrons can penetrate the protective barrier while the unit is operating. Residual activity can expose personnel who enter the treatment room immediately after the treatment has been delivered. The exposures, however, are normally low. Exposures from simulators and other diagnostic imaging equipment used to plan treatments are also normally low [N3].

183. The data on occupational doses in radiotherapy from the UNSCEAR Survey of Occupational Radiation Exposures are included in Table 13. Data from the United Kingdom for specific groups of workers in a sample study are given in Table 21 [H3]. Relatively few beam radiographers, radiotherapists, technicians, or other support staff receive annual doses exceeding 1 mSv. With brachytherapy procedures, some theatre and ward nurses receive over 5 mSv in a year.

184. Worldwide levels of dose and numbers of workers involved in radiotherapy have been estimated from national data using the same extrapolation procedures as previously described. The coverage and scaling of the data were similar to that for nuclear medicine.

185. The annual number of monitored workers, averaged over five-year periods, in radiotherapy worldwide are estimated to have been 84,000, 110,000, 110,000, and 120,000 for the four periods chronologically. (Some 60% of these are employed in countries of the OECD.) The corresponding figures for the average annual worldwide collective effective dose are 190, 180, 100, and 65 man Sv. The last two five-year periods have seen fairly significant reductions in this parameter. While some of this decrease will have been due to general improvements in radiological protection arrangements, a large part of it probably came in brachytherapy, following the replacement of many radium sources by caesium sources and the widespread use of remote afterloading equipment.

186. The annual effective dose to monitored workers worldwide, averaged over five-year periods, fell consistently

over the four periods, with values of 2.2, 1.6, 0.87 and 0.55 mSv (chronological order). This downward trend is reflected in most of the countries reporting, although there are a few exceptions to the general level of average annual effective dose, most notably Pakistan and the United Republic of Tanzania, both of which reported values of about 10 mSv. The average annual dose to measurably exposed workers worldwide was 1.3 mSv, higher by a factor of about 2.7 than that to monitored workers. The fraction of monitored workers, averaged over the reported data, receiving annual effective doses in excess of 15 mSv was small, and indeed only 2% exceeded 5 mSv. This is similar to the figure for nuclear medicine as is the dose distribution for collective effective dose. The values for SR_{15} decreased from about 0.30 for the first period to 0.15 for the latest period. The noted higher average annual individual doses for Pakistan and the United Republic of Tanzania are also reflected in the distribution ratios NR and SR.

E. ALL OTHER MEDICAL USES OF RADIATION

187. The category "all other medical uses of radiation" was intended to cover the expanding uses of radiation within the medical sector that did not fit into the categories of diagnostic radiology, dental radiology, nuclear medicine, or radiotherapy, the principal example being biomedical research. However, previous UNSCEAR reports contained a combined category, "all medical uses of radiation", and this may have led to some confusion in completion of the questionnaire. It was possible to identify and eliminate from this category data that were simply an aggregation of data provided for the various practices. However the potential for a small degree of double counting cannot be eliminated. More importantly, some countries were not able to provide medical sector data in the various categories and opted to put all their data into this category. Indeed it is noticeable in Table 13 that there are some very large monitored populations (in excess of 100,000) in this category, which is unexpected. These data require clarification before they are interpreted; unfortunately, they account for about 68% of the data. In terms of numbers of monitored workers, this category accounts for some 65% of the total reported for all medical exposures. This could have been a significant confounding factor for the estimates made for the various categories of medical use. However, the problem mainly affects the OECD region (Germany and Japan), and the level of reporting over the other countries of the region was sufficient to ensure usable extrapolations in each of the categories. In view of the problem, no attempt has been made to produce world estimates for the "all other medical uses" category.

F. SUMMARY

188. National data on occupational exposures from all medical of radiation averaged over five-year periods are given in Table 14. Worldwide levels of exposure have been estimated from the reported data by extrapolation based on GDP. However it should be noted that in accounting for the lack of data from the United States, the method of estimation for the United States region was modified: the United States values were assumed to be equal to those of the rest of the OECD. This is discussed more fully in paragraph 156. In Figure IX, the collective effective doses from all medical uses of radiation in each country reporting data in 1990–1994 are shown in relation to GDP. The broad correlation between the two quantities is evident, with the degree of correlation generally increasing when consideration is limited to particular regions. For some countries in a geographical or economic region, the normalized collective dose (normalized in terms of the GDP) differed greatly from the average for that region. In most of these cases the values were much smaller than the average, suggesting that the reported data may have been incomplete, that much less use was being made of radiation in medicine, or that much higher standards of protection had been adopted in those countries. Similar observations have been made for the separate practices involving industrial uses of radiation. Notwithstanding these reservations on the completeness of some of the reported data, no attempt has been made to correct for this, and the reported data were all included in the estimation of worldwide levels of exposure. Any errors due to incompleteness of the reported data are unlikely to be significant in comparison with the uncertainty introduced by the extrapolation process itself and by the assumption that all of the reported doses are good surrogates for effective dose.

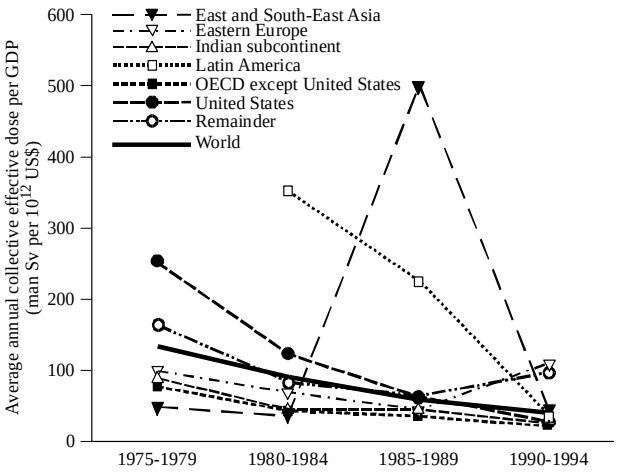

Figure IX. Trends in normalized collective effective dose (to GDP) for all medical uses of radiation.

189. The data on occupational exposures from all medical uses of radiation are presented for various geographic regions and economic groupings in Table 17. Because of its much larger normalized collective dose, the United States has been listed separately from the other OECD countries. Since the normalized collective doses for the respective periods were derived on different price bases (1977, 1983, 1989, and 1994, respectively), direct comparisons cannot be made without appropriate corrections. Within a given period, the normalized collective doses vary by a factor of about 2 between most

regions. The main exception to this in the first three periods was the United States, although some significant variations between periods for different regions are noted. The period 1990–1994 has seen a convergence of the normalized collective doses for the regions; a notable exception is eastern Europe. This may reflect the change in profile of reporting countries in the wake of the political changes taking place.

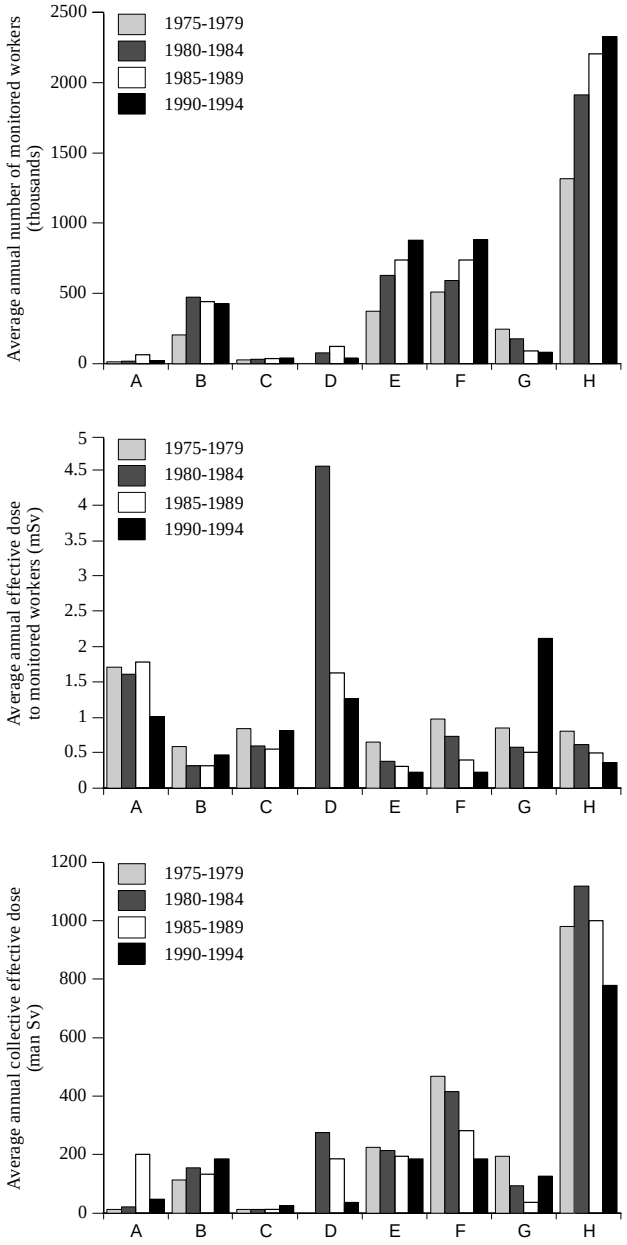

Figure X. Trends in numbers of monitored workers, doses to monitored workers, and collective doses for all medical uses of radiation.

A: East and South-East Asia
B: Eastern Europa
C: Indian subcontinent
D: Latin America
E: OECD except United States
F: United States
G: Remainder
H: World

190. The exposure data for the major regional groupings of countries are illustrated in Figure X. The worldwide annual number of monitored workers averaged over five-year periods is estimated to have increased from about 1.3 million through 1.9 and 2.2 to 2.3 million for 1990–1994. The majority of these workers were employed in the United States or in the rest of the OECD countries. Data for the four periods grouped by medical use sector are given in Table 16. As discussed in paragraph 187, the wording "all other medical exposures" is a confounding factor in the estimation of annual number of monitored workers, averaged over the 1990–1994 period, for the different medical uses. Caution should therefore be exercised in comparing these figures with previous periods. However the ratios between the use sectors are similar to those in the earlier periods and indicate that about 65% of the monitored workers are involved in diagnostic radiology, 20% in dental radiology, and 7% each in nuclear medicine and radiotherapy.

191. The worldwide annual collective effective dose, averaged over five-year periods, remained relatively uniform over the first three periods, about 1,000 man Sv. However, the UNSCEAR 1993 Report [U3] suggested that this might be an overestimate of the worldwide collective dose, with the diagnostic radiography contribution, which was the largest component, suspected of having been overestimated. The worldwide annual collective effective dose, averaged over 1990–1994, is estimated to have been 760 man Sv. This is a significant decrease relative to the previous periods and is consistent with the cautionary comments in the UNSCEAR 1993 Report [U3]. While a number of confounding factors have been identified in the extrapolations, the overall picture across the reporting countries is one of reduced collective doses; this finding provides a degree of confidence in the downward trend.

192. Over the four periods there appear to have been significant changes in the contribution of the different medical uses to the total collective dose. The contribution from diagnostic radiography rose, from 62% to 73% (A higher percentage, 78%, was recorded for 1985–1989, but as noted earlier, the validity of the data is somewhat suspect). The contributions from dental radiology and radiotherapy both decreased significantly, from 12% to 3% and 20% to 10%, respectively. Conversely, the contribution from nuclear medicine increased, from 6% to 14%.

193. The average annual effective doses to monitored workers involved in medical uses of radiation and the doses to monitored workers in each of the categories of medical use have, with two minor exceptions, consistently decreased over the four periods. The exceptions are the rise, from 1.01 mSv to 1.04 mSv, for nuclear medicine between the first and second periods and the insignificant rise for dental radiography, from 0.05 mSv in the third period to 0.06 mSv in the fourth period. The overall reductions over the four periods have been for diagnostic radiography, from 0.94 mSv to 0.50 mSv; for dental radiography, from 0.32 to 0.06 mSv; for nuclear medicine, from 1.0 to 0.79 mSv; and for

radiotherapy, from 2.2 to 0.55 mSv. Over the four periods the value for all medical uses decreased by a factor of about 2.4, to 0.33 mSv. Fewer data have been available for the average annual effective doses to measurably exposed workers, but relative to the preceding period the estimated value for 1990–1994 fell, from 1.7 to 1.4 mSv.

194. For 1990–1994 the fraction of monitored workers worldwide exposed to annual effective doses in excess of 15 mSv was small (less than 1% for each medical practice and for medical uses overall). Indeed for all medical practices, only 1% exceeded 5 mSv. For some individual practices this percentage rose to 2%. The value of SR_{15} decreased from about 0.14 to 0.10 between the first and second periods and then increased to 0.24 for the third. This was attributed to somewhat higher values for China, reported only for the third period. The value for 1990–1994, 0.14, reasserts the downward trend.

IV. INDUSTRIAL USES OF RADIATION

195. Radiation sources, including sealed sources, x-ray machines, and particle accelerators, are used in a number of industrial applications. Among these are industrial irradiation; non-destructive testing (particularly industrial radiography); well logging; luminizing; thickness, moisture, density, and level gauging; tracer techniques; and fluoroscopic and crystallographic analysis of materials. As an example, in France, in 1993, there were 785 known x-ray generators and 850 gamma-radiography devices being used for non-destructive testing [V1]. In addition, there were 16 industrial accelerators, 85 irradiators, more than 10,000 gauges, and 200 x-ray fluorescence analysers. Because of the many different occupations involved and the ways in which exposures are categorized, it is difficult to obtain comparable statistics in different countries. Most exposures in industrial uses of radiation are small, which contributes to the lack of detail in recorded data. In the UNSCEAR 1993 Report [U3], exposures were considered for those groups of workers that generally experience higher doses: industrial radiographers, luminizers, and well loggers. Workers involved in isotope production and workers employed and monitored at education and research institutes were also assessed. The following categories are used in the survey of data for 1990–1994: industrial irradiation, industrial radiography, luminizing, radioisotope production, well logging, accelerator operation, and all other industrial uses. For the three previous periods the exposure of workers in educational establishments and tertiary education was included within the general category of industrial uses; in this Annex these exposures are included within a miscellaneous category in Chapter VII.

196. Differences may exist in the procedures used in various countries to group workers occupationally, which limits the validity of direct comparisons between data compiled in different countries. Where these limitations may be important, they are identified. The extent to which valid comparisons can be made between countries is also influenced by differences in the approaches used to measure and report occupational exposures, e.g. the type of dosimeter used, its minimum detectable level (MDL), the dose entered into records when the measured dose is less than the MDL, and doses assigned for lost dosimeters. These differences and their implications for the validity of comparisons between data were discussed in Chapter I. The approaches used in measuring and reporting occupational exposures in each of the countries for which data were reported are summarized in Table 2. Where important differences in approach are apparent, caution should be exercised in making direct comparisons between data.

197. National data on occupational exposures arising from the industrial use of radiation for the categories mentioned above are given in Table 22. From the data set available, worldwide extrapolations were possible only for industrial radiography and radioisotope production. These were derived using extrapolations within regions based on GDP, using the procedure described in Section I.E. The degree of extrapolation needed varied, and while there was a general correlation with GDP, this was less robust than for the data on medical uses (see Figure XI). The reported data, broken down by practice and region, are given in Table 23. National data for the various categories were aggregated by country to give data on exposures to workers from all industrial uses of radiation; they are presented in Table 24. Worldwide estimates of exposure were derived using extrapolations within regions, as above, but the data from the United States were limited and the correlation with GDP was poor. The Committee therefore used OECD figures as a surrogate, as was done for exposures from medical uses.

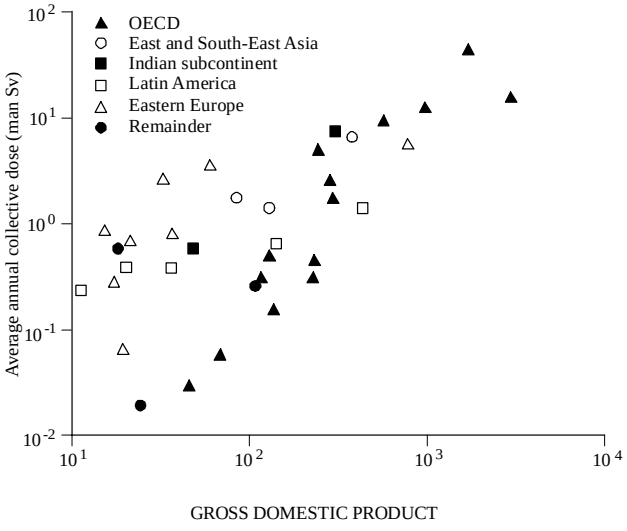

Figure XI. Correlation of collective dose with GDP for industrial uses of radiation.

A. INDUSTRIAL IRRADIATION

198. There are currently 160 gamma-irradiation facilities and over 600 electron-beam facilities in operation throughout the world [I3]. The most widespread uses of these facilities are the sterilization of medical and pharmaceutical products, the preservation of foodstuffs, polymer synthesis and modification, and the eradication of insect infestation. Gamma and electron irradiation facilities have to be constructed such that during normal use any radiation exposure of workers will be very slight. The product doses required are extremely high, and the source activities or beam currents are correspondingly high. For gamma facilities the source would typically be ^{60}Co in the petabequerel (PBq) range; some ^{137}Cs sources are also used. Dose rates in the irradiation chamber would be of the order of 1 Gy s^{-1}, and in some cases there is a need to protect against radiogenic heating that could cause fires.

199. Clearly, because such high dose rates are involved there is a need for sophisticated engineered safety systems that meet the defence-in-depth principle [I3, I8]. The shielding provided by such facilities is necessarily significant, and during normal usage the exposure of workers should be very low. However, significant exposure may result from loss of control over, or damage to, the radiation source, and in extreme cases, the exposures may be sufficient to cause serious injury or even fatalities in the short term. Accidents at these facilities are discussed in Chapter VII.

200. This category of work was not specifically considered in the previous UNSCEAR Survey of Occupational Radiation Exposures [U3]. The available data, given in Table 22, are limited and cover just 15 countries. Of crucial importance is the fact that there are few data from the large industrialized countries, where the greatest number of irradiators are located. Typically, the number of workers in an irradiation facility is relatively small, although the data from Japan indicate a remarkably large number of monitored workers, some 55,000. This accounts for 96% of all the reported monitored workers, and therefore any comparisons should be treated with caution. The data set was not sufficient to allow a reliable worldwide estimate. However, a crude estimate based on a global GDP extrapolation would indicate a monitored workforce of a few hundred thousand and an annual collective effective dose of a few tens of man sieverts worldwide. Thus, the lack of data for this sector is unlikely to affect overall industrial use estimates.

201. For the reported data, the average annual individual effective dose per monitored worker ranges from zero to 1.3 mSv, with an overall average of 0.10 mSv. The corresponding figures for measurably exposed workers range from 0.15 to 2.8 mSv. The latter figure is from Japan and dominates the average annual effective dose to measurably exposed workers, 2.3 mSv. The values of NR for Japan (and overall) are low, indicating that few workers receive any significant exposure. The corresponding values of SR show a significant component of collective dose in the upper levels of individual dose. The raw data for SR_{15} and NR_{15} indicate that, distributed reasonably uniformly over the five-year period, an aggregate of 268 workers received 10.6 man Sv, equivalent to some 50 persons each receiving 40 mSv.

B. INDUSTRIAL RADIOGRAPHY

202. Industrial radiography is performed under two quite different sets of conditions. In the first, it is carried out at a single location, usually in a permanent facility that has been designed and shielded for the purpose; in this case, items to be radiographed are brought to the facility. In the second, the radiography is carried out at multiple locations in the field, in which case the radiographic equipment is brought to the location where the radiograph is required, often referred to as site radiography. There are often significant differences in the degree of control that can be exercised in the two situations. However, few of the data reported to the Committee distinguish between the two situations.

203. Both x-ray equipment and sealed sources are used in industrial radiography. The most common sealed sources are ^{192}Ir (activity between 1.8 and 4.4 TBq), ^{60}Co (activity of the order of 0.3 GBq), and ^{137}Cs (activity between 0.3 and 80 GBq). These can be used in three basic formats. The oldest format is direct manual manipulation, which either uses handling equipment or is an integral part of a shielded “torch”. This format, which was prevalent in the 1970s but declining in the 1980s, still has some usage. Another format has the source in a shielded container; the source can be rotated or moved to produce a collimated beam. This format, too, is declining in usage. By far the largest amount of gamma radiography is carried out using remote exposure containers. Typically, the source is on the end of a drive cable that can be controlled from 10 or so metres away, so that the source is projected down a flexible tube to the radiography position, where a collimator is normally positioned to reduce the radiation dose to the operators. These devices are portable and are widely used for site radiography. They are also used in fixed facility radiography, where they can be integrated into the installed safety systems, although this is not always done. Some installed systems use pneumatic or electrical drives. The x-ray sets in industrial radiography typically vary in applied voltage from 60 to 300 kV, although there are some 400-kV units. In addition, there are a smaller number of linear accelerators, typically in the range 1–8 MV. These are mostly in fixed facilities with installed safety systems, but there are a few mobile units.

204. In site radiography, the working conditions are such that some routine exposure is expected. For gamma radiography this mostly derives from exposure while the source is in transit from the shielded container to and from the collimator position; hence, positioning of the control position is relevant. If a collimator is not used, doses from primary radiation and scattered radiation will be larger.

205. In fixed radiography facilities, the shielding and engineered safety systems should ensure low doses. However, variable standards of design for safety systems, or poor maintenance and degradation of the systems, may give rise to incidents that, if not quickly recognized, can lead to exposures above the dose limit or even the levels that might result in deterministic effects.

206. Site radiography presents a number of radiological safety challenges. The work is often undertaken in remote, difficult, or even hostile environments; in addition, supervision tends to be poor, it is a highly competitive business, and the equipment must be robust. A common failure mode in gamma radiography is for the source to become detached from the drive cable but not to be detected immediately, owing to poor or non-existent monitoring. In short, in addition to the possibility of high routine doses, there is the possibility of equipment and procedural failures, a potentially lethal combination. Once sources are removed from control or discarded, they can be the cause of accidental exposures of members of the public (see Chapter VII).

207. Worldwide levels of dose have been estimated from national data by extrapolation within regions based on GDP. The countries reporting data accounted for about 35% of the worldwide total in the first five-year period, increasing to 65% in the third and 66% in the fourth. On average, therefore, the reported data have been scaled upward by a factor of about 2 but with considerable variation about this average for particular periods and regions. The superficial similarity in the percentage of countries reporting for the third and fourth periods warrants closer examination. While there is generally reasonable correlation of the data with GDP, the data for the United States in the fourth period are radically different from the data for the third; 10,000 monitored workers with an annual collective dose of 5.75 man Sv and 274,000 monitored workers with a collective dose of 101 man Sv, respectively. The estimates of numbers of workers and doses in industrial radiography worldwide are given in Table 22, with trends over time also shown in Table 25 and Figure XII. The annual number of monitored workers in industrial radiography, averaged over five-year periods is estimated to have increased from about 70,000 over the first period to about 110,000 over each of the last three periods, with some 10% variation about this value. The average annual collective effective dose is estimated to have increased from about 190 man Sv in the first period to about 230 man Sv in the second, then to have decreased to 160 and 170 man Sv in the third and fourth periods. For the first three periods, about 50% of the collective dose was estimated to have occurred in the countries of the OECD, with about a further 25% to 30% in eastern Europe. For the fourth period the contribution from the OECD countries dropped to 40%.

208. The worldwide annual effective dose to monitored workers averaged over five-year periods fell progressively, from about 2.6 mSv in the first period to 1.4 mSv in the third. However, for the fourth period there was a small increase, to 1.6 mSv. The validity of this figure is confounded by the sparse data from the United States. If it is assumed, as was done elsewhere in this Annex, that the United States approximates to the rest of the OECD, the corresponding figure would be 1.4 mSv, identical to that for the third period. The implication is that at best the worldwide value for the annual effective dose to monitored workers is not falling. The national data show great variability, with some countries showing reductions and others showing increases. Many countries show dose distributions with low values for NR but with relatively high values for SR_{15} and SR_{10}. As with well logging, these ratios suggest that a small percentage of the workforce

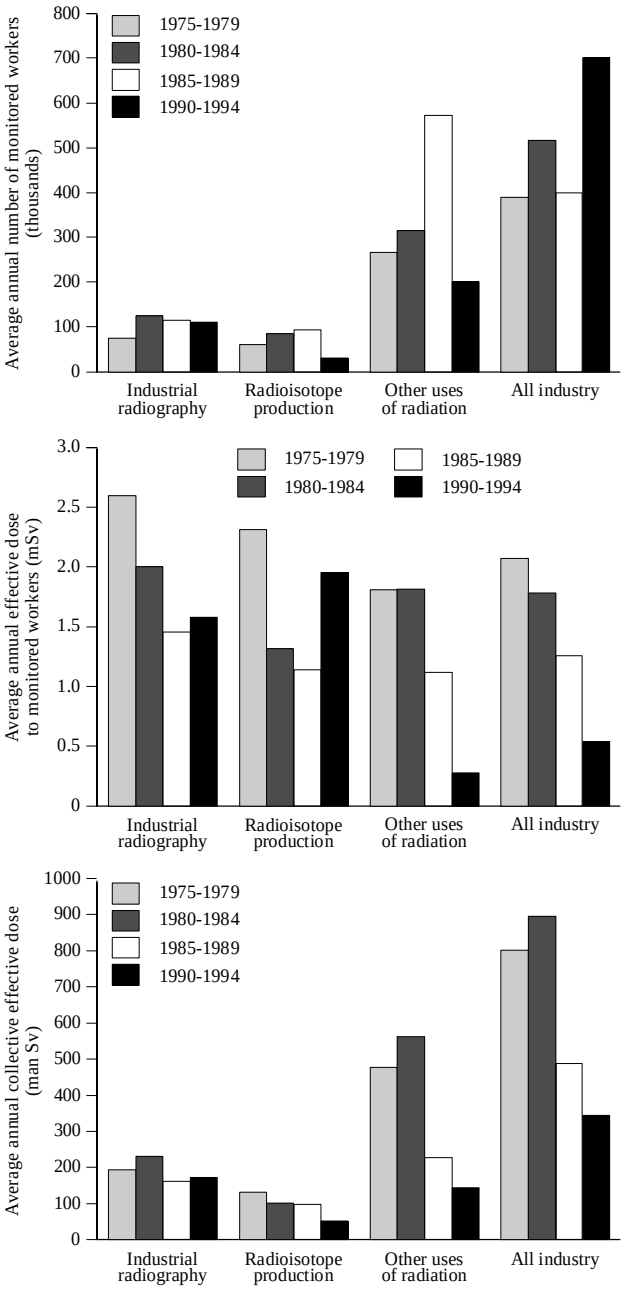

Figure XII. Trends in numbers of monitored workers, doses to workers, and collective doses for industrial uses of radiation.

receives doses, often routinely, above 10 mSv or 15 mSv. These individuals are likely to be involved in site radiography. At a national level the profile of doses can be significantly affected by industrial/commercial activity profiles. For example, large investments in power stations (particularly nuclear), pipeline construction, and the petrochemical industry can result in increased demands for site radiography, which non-destructive testing companies respond to with increased staff and activity; this activity tapers off when industrial investment starts to languish.

209. In previous periods relatively few data were available on average doses to measurably exposed workers as opposed to monitored workers, and no attempts were made to estimate a worldwide average. However, more relevant data have been provided for the fourth period, and the worldwide average annual dose to measurably exposed workers is estimated to be 3.2 mSv. This estimate should be treated with caution as the national data in Table 22 show considerable variation up to about 20 mSv.

210. Dose information for industrial radiographers in the United Kingdom from 1986 to 1994 is given in Table 26 [H1, H2]. This shows that, contrary to the trends for other groups of workers, there has been little or no reduction in the number of workers exceeding specified dose levels. Indeed in the latter part of the reporting period and subsequently, industrial radiography replaced the nuclear industry as the industry with the most exposures in the dose ranges above 20 and 50 mSv.

C. LUMINIZING

211. Radioactive materials have been used in luminizing for decades. The number of workers involved has been low, with fewer than 1,000 reported in each of the periods. There has with time been a shift away from the use of radium to tritium and, to a lesser extent, ^{147}Pm. Tritium is used in two forms: mixed with a phosphor in a paint and as a gas enclosed in a phosphor-lined, glass-walled tube.

212. The data for 1990–1994 reported in Table 22 come from only three countries and are not comprehensive enough to enable a reliable estimate of the worldwide levels of dose from the industry. The reported number of monitored workers is less than 100; they received a collective dose of 0.03 man Sv and an average annual dose of 0.38 mSv. The figures reported for the preceding period were 540 monitored workers, a collective dose of 1.45 man Sv, and an average annual dose of 2.7 mSv. Historically, the doses to workers involved in luminizing were high, but recent years have seen a significant reduction. Indeed it now seems likely that, worldwide, fewer than 1,000 workers are involved and that luminizing contributes less than 1 man Sv to worldwide occupational exposure. It may therefore not be relevant to treat these as a separate category in future reviews but to include them instead in the "other industrial uses" category.

213. Luminizing is one of the oldest industrial uses of ionizing radiation, and while direct occupational exposure may be low, there are other exposures from the legacy of this type of work. The limited controls in place during the early widespread use of radium have left many contaminated sites around the world, some known and others just coming to light. The decontamination and remediation of these sites have implications for occupational exposure, but the data are very scarce and are likely to be subsumed in broader categories. Another aspect of luminizing is the fact that there are many millions of luminized items that can end up in the public domain.

D. RADIOISOTOPE PRODUCTION AND DISTRIBUTION

214. Radioisotopes are produced for a great variety of industrial and medical purposes. The main source of occupational exposure in radioiosotope production and distribution is external irradiation; internal exposure may be significant in some cases, and arrangements are then made for personal monitoring. In general, however, internal exposures have not been included in reported statistics for occupational exposure, except in more recent years, and even then their inclusion is far from universal. Reporting conventions for workers involved in radioisotope production may also vary from country to country (e.g. whether the reported doses include only those arising during the initial production and distribution of radioisotopes or whether they also include those arising in the subsequent processing, encapsulation, packaging, and distribution of radionuclides that may have been purchased in bulk from elsewhere), and this may affect the validity of comparisons between reported doses.

215. Worldwide levels of exposure have been estimated from reported national data, using extrapolation within regions based on GDP. The data set is smaller than that for industrial radiography, and on average the scale factor used is higher, about 3, with considerable variation about this figure. Nevertheless, it has been possible to make an estimate of worldwide exposure. The number of workers involved in radioisotope production around the world, averaged over five-year periods, increased from about 57,000 in the first period to about 88,000 in the third period, reflecting the growing use of radioisotopes in both industry and medicine. However, the estimate for the fourth period is only about 24,000 workers monitored. Data for previous periods was dominated by data from the United States (about 30,000 monitored in the third period). There are no signs that the market for radioisotopes is declining, and even if the United States' contribution in the fourth period was the same as in the third, the number of monitored workers would still be only 50,000. It is therefore concluded that there has been a genuine reduction in monitored workers. The industry is now mature and well established, with multinational companies replacing the often nationally focused entities that prevailed in earlier years. This has meant some

rationalization of production and economies of scale, reflected in the declining numbers of exposed workers.

216. Despite the above-mentioned increases over the first three periods, the estimated worldwide annual collective effective dose dropped from more than 130 man Sv in the first period to about 100 man Sv in both the second and third. The estimate for the fourth period is 47 man Sv, a reduction by a factor of about 2. While the estimated value may be low as the result of a smaller data set, when the error margins over time are taken into account, the data would be consistent with a compound reduction of 30% per period. Alternatively, the reduction by a factor of 2 relative to the last period would be consistent with the emphasis given to ALARA in the late 1980s by international bodies [E3, I5, I12] having worked its way through to implementation in the fourth period. Overall, the estimated value is considered valid. As in previous periods, about two thirds of these collective doses are estimated to have occurred in OECD countries, with most of the remainder occurring in eastern Europe and southern and South-East Asia.

217. The annual dose to monitored workers worldwide averaged over five-year periods fell, from about 2.3 mSv in the first period to about 1.1 mSv in the third period. The estimate for the fourth period, 1.9 mSv, indicates a reversal of this trend. While the limited data set must cast some doubt on this figure, it would be consistent with the significant reduction in the estimated workforce. More data were available for the fourth period on average annual doses to measurably exposed workers, allowing a worldwide estimate of 2.9 mSv. Some two thirds of the monitored workers are estimated to have received measurable doses. This is a fairly consistent pattern across the reporting countries, and the dose profiles indicated by the NR and SR values are similar to those for industrial radiography.

218. In the manufacture and processing of radionuclides there is the potential for both internal and external exposure. It is not always apparent, however, from the reported data whether the internal component was significant and whether it was included in the dose estimates. The data for the United Kingdom from 1985 and for Finland from 1987 onward include doses from intakes of radionuclides. In general, the contribution to the total dose was reported to be a few percent. It would be useful if in future all data could clarify the component parts.

E. WELL LOGGING

219. Well logging has been identified in some countries as an industrial use that can lead to higher doses to workers than other industrial uses. This is sometimes attributed to the manual manipulation of sources in small spaces, such as on oil rigs. Both gamma and neutron sources are used in well logging, but the contribution from each to the reported doses is generally not indicated.

220. The data on well logging, presented in Table 22, are not sufficient to enable a reliable estimate of worldwide levels of dose. Nevertheless, a review of the data suggests that a scaling factor of 10 used on the total reported data could set an upper bound for the likely worldwide figures. This suggests a worldwide annual collective effective dose of a few tens of man sieverts, or less than 10% of the overall exposure from industrial uses.

221. The annual effective dose to monitored workers averaged over the reported data for 1990–1994 is 0.36 mSv, continuing the trend observed over the three previous periods, for which the corresponding figures were 1.3, 1.2, and 1.1 mSv. Although this is a relatively low figure, there was considerable variation between countries; Slovakia, for example, reported a value of 5.3 mSv. The average annual effective dose to measurably exposed workers based on the aggregated reported data was 0.79 mSv for the fourth period. The distribution ratios NR and SR indicate that while a majority of monitored workers get low doses, some in this industrial sector receive more significant doses, although not as high as in, for example, industrial radiography or radioisotope production.

F. ACCELERATOR OPERATION

222. Consideration is limited here to occupational exposures arising from accelerators used for nuclear physics research at universities and national and international laboratories. Accelerators (generally of somewhat smaller size) are increasingly being used for medical purposes, i.e. therapy and radiopharmaceutical purposes; however, the exposures arising from them are more appropriately associated with exposures arising from the medical uses of radiation. Similarly, accelerators are also found in radiography and commercial radioisotope production, but again these are dealt with under those work categories. Most exposures from accelerators result from induced radioactivity and occur mainly during the repair, maintenance, and modification of equipment. They come mainly from gamma radiation from the activation of solid surrounding materials by penetrating radiation. The potential for internal exposure in the normal operation of accelerators is slight, and doses via this route are negligible in comparison with those from external irradiation.

223. Early high-energy accelerators used internal targets to produce either radioisotopes or secondary beams of normally unstable particles. Very high levels of activation products were produced in the region of the targets, and typical annual collective doses per accelerator were 1–2 man Sv before 1960; this is still true for many of the early cyclotrons that are still in operation. Between 1960 and 1980, beam extraction techniques were improved, which led to reduced levels of activation products; these reductions were, however, largely offset by the continuing increases in beam power.

224. In the 1980s, two developments had an important influence on occupational exposures at accelerators. The first was the increasing importance of colliding beam techniques for the production of events of interest to the particle physics community. Average beam intensities, as measured by the number of particles accelerated per day, are several orders of magnitude lower than those used in fixed-target physics experiments. Consequently, the production of activation products has been greatly reduced, and this is reflected in the exposures of maintenance personnel. The second development was a move towards heavy ion operation, where again the accelerated beam intensities are several orders of magnitude lower than those with proton acceleration. This has also led to a decrease in activation products and, consequently, in exposures during maintenance.

225. As a consequence of these technical developments and the greater emphasis given generally to ALARA programmes at accelerators, there were large reductions in the collective effective doses at large accelerator laboratories between the mid-1970s and the mid-1980s [P2]. Decreases in the annual collective dose, from about 0.1 to 0.01 man Sv, were experienced at Deutches Elektronen Synchrotron; from about 0.2 to 0.02 man Sv at Daresbury Nuclear Physics Laboratory; from about 5 to 1.5 man Sv at the European Organization for Nuclear Research; and from about 0.5 to about 0.2 man Sv at the Lawrence Berkeley Laboratory.

226. The available data, shown in Table 22, cover only some 1,300 monitored workers from eight countries and are not complete enough to permit a reliable estimate of the world-wide dose from accelerators; however, the sums (or averages) of the available data are shown. The average annual collective effective dose for the reported data is about 1.0 man Sv, compared with about 7.4 man Sv for the first period and 3.7 and 3.5 man Sv for the intervening periods. The data set does not permit drawing any conclusions beyond that the levels of annual collective dose are consistent and that the contribution to worldwide doses from all industrial uses is likely to be insignificant. The average annual effective dose to monitored workers for the reported data is 0.75 mSv, slightly higher than the 0.62 mSv reported for the previous period. Again, undue significance should not be attached to this apparent increase, and it would be more appropriate to conclude that the data are broadly consistent with those for previous periods.

G. ALL OTHER INDUSTRIAL USES

227. There are many other uses of radiation in industry, e.g. in soil moisture gauges, thickness gauges, and x-ray diffraction, but occupational exposure data for these are not, in general, separately identified or reported. The number of workers potentially exposed in these other uses may substantially exceed those in the few occupations for which data have been separately presented in this Chapter. The average exposure levels of workers involved in other uses of radiation are, in general, small. However, because of the way in which the doses are aggregated, they may disguise somewhat higher average doses in particular occupations. The only way to ascertain the existence of occupations, or subgroups within occupations, receiving doses significantly in excess of the average is for those who compile data to inspect the data periodically. Such inspection is to be encouraged.

228. As is the case for the comparable general category under medical uses, there are several entries of tens of thousands of monitored workers, e.g. in Germany, Japan, and the United Kingdom. These entries appear in this Section because the national systems for collecting data do not readily permit desegregating the data into the categories used in this review. Nevertheless it is important that these data are captured as they feed into the next Section.

H. SUMMARY

229. Table 24 shows the national data from all industrial uses of radiation grouped together. The data are more complete than for the separate categories of industrial use of radiation, but as with the data for medical uses they suffer from limited data from the United States, which is important in the estimation of worldwide exposure. While the normal method of regional extrapolation based on GDP (as outlined in Section I.E) was considered acceptable for estimating worldwide industrial radiography and radio-isotope production, its validity was dubious when applied to all industrial uses. The total reported data for the United States during 1990–1994 covered some 10,000 monitored workers who experienced an annual collective effective dose of 25 man Sv. The corresponding figures for 1985–1989 were 274,000 monitored workers and 150 man Sv. While some reductions may have occurred, they are extremely unlikely to have been this large.

230. The Committee considered alternative methods of estimating the values for the United States. The region with the most similarities to the United States is the rest of the OECD countries. The UNSCEAR 1993 Report [U3] showed the collective effective dose per unit GDP (man Sv per 10^{12} United States dollars) for the United States divided by that for the rest of the OECD to be within 10% of 2.0 for each of the earlier periods. Given that the ratio of the GDPs for 1990–1994 is approximately the inverse of this, namely 0.5, it appears reasonable to carry out extrapolations of world estimates on the basis that the figures for United States can be taken to be equal to the figures for the rest of the OECD. World estimates using this approach are given in Tables 25 and 27. For comparison, world estimates based on the method in Section I.E are given in brackets in these tables. It is important to note a significant difference between the data quoted for the first three periods in Tables 25 and 27. The UNSCEAR 1993 Report included exposures to people involved in education under industrial uses, whereas this Annex treats education separately. Table 25 summarizes worldwide exposure, by practice, from industrial uses, and for the first three periods it was easy to recalculate the data

without the contribution from education, permitting a suitable comparison with the data for 1990–1994. However, for Table 27, which summarizes the contribution of the different regions, such readjustments are not readily achievable because of the way earlier data were configured. The worldwide totals for the first three periods include a contribution from education and are therefore different from those quoted in Table 25. Thus caution needs to be exercised in comparing data over the various periods.

231. Using data adjusted for the non-inclusion of educational uses, the annual number of monitored workers involved with industrial uses of radiation, averaged over five-year periods, is estimated to have been 390,000, 510,000, 400,000, and 700,000 from the first to the fourth periods. The uncertainty associated with these figures does not allow inferring a clear upward trend; however, such a trend would be consistent with increased global industrialization. Even so, in each of the periods the OECD (including the United States) accounts for a vast majority of the exposed workers. The average annual collective doses, after an initial rise from 800 to 900 man Sv over the first two periods, dropped to 490 and then 360 man Sv in the third and fourth periods, respectively. In general, some three quarters of the dose comes from OECD countries.

232. The annual effective dose to monitored workers averaged over five-year periods fell consistently over the four periods, with values of 2.1, 1.8, 1.2, and 0.51 mSv (in chronological order). This downward trend is evident for most countries and regional groupings, but there is considerable variation. For the last period, data were available on the average annual effective dose to measurably exposed workers, giving a worldwide value of 2.2 mSv. This is greater by a factor of 4.5 than the value for monitored workers. This factor is larger than that for reactor workers or medical workers and is perhaps indicative of better defined subgroups of workers, particularly in industrial radiography and well logging, who can routinely receive higher exposures.

233. While the confounding factor of educational uses means that care must be exercised when comparing the data in Table 27 between periods, it is instructive to look at the normalized collective dose values in man Sv per 10^{12} United States dollars. Although there are region-to-region variations in the magnitude of the change, there is a consistent general downward trend. The worldwide values were 120, 72, and about 30 man Sv per 10^{12} United States dollars in the first, second, and combined third and fourth periods, respectively.

V. NATURAL SOURCES OF RADIATION

234. Since natural radiation is ubiquitous it is necessary to direct attention to the highest exposures and to those cases where actions to reduce or limit exposures are most likely to be effective. Enhanced levels of natural background radiation are encountered in many occupational settings, especially underground mines. Mining involves a large number of workers, and although data are more limited than those for occupational exposures to man-made sources, the annual collective effective dose has been estimated to be twice as large [U3]. There is less awareness of exposures from natural radiation in other settings, and often there are no regulatory requirements to monitor and record these occupational exposures. Consequently, surveys are necessary at the national level to determine the scale and nature of the exposures. A general review of exposures from natural sources of radiation is given in Annex B, "*Exposures from natural radiation sources*". The UNSCEAR Survey of Occupational Radiation Exposures specifically sought information on exposures of aircrew to cosmic rays; exposures of coal miners, primarily to radon decay products; and exposures of miners of minerals other than coal. Significant individual exposures to radon decay products can also occur in other workplaces, and there may also be significant exposures to long-lived natural radionuclides in dusts during the handling and processing of bulk quantities of minerals and other materials. Uranium mining is not considered here but is included instead as part of the nuclear fuel cycle (Chapter II).

A. COSMIC-RAY EXPOSURES TO AIRCREW

235. In the course of their work, aircrew and others who fly frequently are exposed to elevated levels of cosmic radiation of galactic and solar origin and secondary radiation produced in the atmosphere, aircraft structure, etc. This has been recognized for some time, and the exposure of aircrew was estimated in the UNSCEAR 1993 Report [U3]. The growing interest in these exposures in recent years is due to three considerations. The first is that the relative biological effectiveness of the neutron component of aircrew exposure was being underestimated by the definition of the quantity tissue dose equivalent and by the specification of a quality factor [I19, N1]. Secondly, subsonic commercial aircraft, particularly business jet aircraft, can attain higher altitudes [W2]. Finally, ICRP recommended in its Publication 60 [I12] that the exposure of aircrew in jet aircraft should be treated as occupational exposure. Particularly worthy of note is the study of the European Dosimetry Group (EURADOS) [E1], which reviewed the data on exposure of aircrew to cosmic radiation in response to the ICRP recommendations.

236. Dose rates from cosmic radiation vary with altitude, latitude, and phase of the solar cycle. For subsonic flights at altitudes up to 13 km, the dose equivalent rates increase as a function of altitude and latitude. Available measurements were compiled in the review cited above [E1], and a figure

illustrating the results is included in Figure III of Annex B, "*Exposures from natural radiation sources*". The data are given in the previous quantities; it is estimated that effective doses calculated using the new quality factors from the ICRP recommendations [I12] would be similar. The UNSCEAR 1993 Report [U3] gave the results of a worldwide measurement programme on Lufthansa airplanes. Most flight altitudes were in the range 10 to 11.9 km, where effective dose equivalent rates were less than 5 μSv h^{-1} and 8 μSv h^{-1}, respectively. These values are roughly in agreement with current estimates. The more recent review of the exposure of aircrew [E1] indicates that the effective dose rate at an altitude of 8 km in temperate latitudes is typically up to about 3 μSv h^{-1}. At 12 km, the value would be about twice this. These values may be compared with those given in Annex B, "*Exposures from natural radiation sources*". The equivalent dose rates were noted to be highly dependent on the flight profile, ranging from 0.2 μSv h^{-1} for a flight of 0.4 hours at a cruising altitude of 3.6 km to 5.8 μSv h^{-1} for an Athens-New York flight of 9.4 hours at a mean altitude of 12 km [O6].

237. The following broad conclusions have been drawn from the data from measurements and evaluations of exposures at aircraft altitudes [E1]:

(a) location within an aircraft does not affect the exposure level by more than ±10%;
(b) going from the equator to either pole, the dose rate increases up to a latitude of about 50° and remains approximately constant at higher latitudes. The increase is greater for the high-LET component (a factor of 3 to 5) than for the low-LET component (a factor of 1.5 to 2.5);
(c) the total dose equivalent rates increase with flight altitude for all latitudes;
(d) values of the total dose equivalent correlate well with the variation in cosmic radiation intensity due to the solar cycle of about 11 years, being higher at times of minimum solar activity and vice versa; the values range from about 0.8 to 1.2 of the mean; and
(e) the relative contributions of the high- and low-LET components of the dose equivalent are broadly similar at temperate latitudes and at normal flight altitudes.

238. Drawing on the measurements and evaluation of the EU research programme [B5, E1, O7, S5, T1], for flights at temperate latitudes at a typical altitude of 10.6 km (35,000 ft) and for average solar activity, it can be estimated that a total time at altitude of about 200 hours is needed to accumulate 1 mSv. Near the equator and at this altitude, the time needed is about 400 hours. At an altitude of 11.8 km (39,000 ft) these times are 150 and 300 hours, respectively, and at an altitude of 10 km (33,000 ft) 250 and 500 hours. If it becomes necessary to assess individual doses, this may be done by combining roster information with "route doses". Route doses may be measured or calculated using computer programs developed for this purpose for particular routes and flight profiles. For example, a flight from northern Europe to the eastern seaboard of the United States, a flight time of about 7 hours will result in an effective dose between 30 and 40 μSv. For a longer flight, say from northern Europe to Japan, the total effective dose is about 50 to 70 μSv. Transatlantic flights at the altitudes used by supersonic aircraft give effective doses similar to those for subsonic aircraft, the higher dose rates being offset by the shorter flight times. Estimates of effective dose from cosmic radiation for typical flight routes are given in Table 28.

239. The data on occupational exposures in civilian aviation from the UNSCEAR Survey of Occupational Radiation Exposures are given in Table 29. Only three countries, Bulgaria, Finland, and the United Kingdom reported data, and in each case without any dose distribution ratios. Of these, the United Kingdom has the most extensive air transport industry, and it is useful to look in more detail at the derivation of the United Kingdom submission. Available data indicate that aircrew on long-haul flights may be airborne for 600 hours in a year [D1], during which they are estimated to receive an annual effective dose of 3 mSv [H3]. To take account of short-haul flights as well, an annual average of 500 hours aloft was assumed in deriving the average annual effective dose of 2 mSv and the collective effective dose of 50 man Sv given in Table 29. In the UNSCEAR 1993 Report [U3], an annual flying time of 600 hours was estimated for aircrew in some European countries and about a 50% longer flying time in the United States. Based on an average annual effective dose equivalent of 3 mSv to about a quarter of a million aircrew worldwide (appropriate for the late 1980s), an annual collective effective dose equivalent for all aircrew of 800 man Sv was calculated. From the data available there would appear to be no substantive change to any of these parameters, so this estimate can be taken to apply also to 1990–1994. A number of subgroups and situations deserve mention and are discussed below.

240. The doses to other persons, such as couriers, is much more difficult to estimate. Based on an analysis carried out at London airport [G1], it was determined that some professional couriers undertook 200 journeys a year, implying 1,200 flying hours and an annual effective dose of 6–10 mSv. The number of such individuals is unknown, but the annual collective effective dose must be a small fraction of that to aircrew. In Germany, approximately 20,000 persons other than aircrew who are frequent flyers are estimated to receive annual doses above 1 mSv [S2].

241. The Concorde carries an in-flight warning meter, and this has permitted the accumulation of a large amount of data on exposure at typical supersonic flight altitudes. The average total dose equivalent rate in 1976–1983 was 11.2 μSv h^{-1}; average values reported for 1988, 1989, and 1990 were 12.2, 11.6, and 10 μSv h^{-1}, respectively, for altitudes of about 18 km [D1]. Values measured by Soviet scientists in 1977 for supersonic aircraft, ranging from 10 to 12 μSv h^{-1}, agree with these values [A1]. The relative contributions of both components are about the same as for subsonic flight altitudes. While the crew of supersonic aircraft such as the Concorde are subject to the highest dose rates experienced in civil aviation, such crew do not

necessarily receive the highest doses. British Airways data for Concorde flight crew in 1994 indicated an average duty time of 382 hours in 12 months, and for the subgroup with the longest flight time, engineers, the average duty time was 403 hours [E1]. Thus, average annual effective doses to aircrew would be about 3 mSv.

242. Elevated exposure rates may be associated with solar flare events. At maximum solar activity, several dozen flares may be observed in one day. However, only a small fraction of flares (about 3%) produce high-energy fluences, and only a small fraction of these cause increased intensity of cosmic radiation [L1, W1]. In years of minimum solar activity, on average only one significant event in a year is observed. The largest events take place at the end of the period of maximum solar activity. The rise in dose rates associated with a flare is quite rapid, usually a matter of minutes, and the duration may be hours or longer. The influence of solar flares on the radiation situation at the altitude of air transport has been thoroughly reviewed [F1]. It was found that the upper limit of the dose equivalent rate during the February 1956 flare was about 30 mSv h^{-1} at 20 km altitude and 10 mSv h^{-1} at 10 km. That flare was the most important of known events, and since then dose rates associated with flares have been very much smaller. O'Brien [O1] calculated the additional contribution to dose equivalent for regular polar flights over the period February 1984 to July 1992, during which 14 periods of energetic solar activity were observed. At 12 km, the additional contribution to the dose equivalent was calculated to be 3% and at 18 km, 7%. In 1993, a year of medium solar activity, the maximum annual effective dose to an individual on Lufthansa flights across the North Atlantic was estimated to be 4.5 mSv [S2]. Altogether, 25,000 persons work as flight personnel in Germany. Most of them are estimated to be exposed to annual doses of 1–6 mSv. For a relatively small number of persons (of the order of 100), annual exposures above 6 mSv are estimated to occur at times of low solar activity on some routes (high geomagnetic latitude and high altitude). Exposure during space flight was reviewed in the UNSCEAR 1993 Report [U3]. Some further information on exposure in space flight is given in the Proceedings of the International Workshop on Space Radiation Damage and Biodosimetry, held at Houston, Texas, in September 1996 [C8]. One paper reviewed the sources of charged-particle radiation that contribute to radiation exposure on manned spacecraft and provided estimates of the dose rate expected for the International Space Station; these estimates are based on measurements made on the Mir orbital station [B4]. Another paper presented the result of a biodosimetry analysis for the space flight Mir-18 using fluorescence *in situ* hybridization (FISH) techniques [Y1].

243. In summary, the data indicate that the average annual effective dose to aircrew is typically 1–2 mSv for those on short-haul flights and 3–5 mSv for those on long-haul flights. Few aircrew will exceed these values because there are laws regulating flying hours. A separate group, couriers, may spend more time in flight over a year but even so are unlikely to exceed 10 mSv. Worldwide annual collective effective dose to aircrew from cosmic ray exposure is estimated to be 800 man Sv. This estimate is based on the extrapolation of limited data, and there is a need to extend the data for future assessments. There are now good data on typical exposure rates and computer programmes that account for a range of variables and allow reasonable estimates of route doses. Also, for legal reasons logs are kept of the hours and routes flown. Bringing these two data sets together should in the future allow much better estimates of dose profiles. This matter has been given impetus by the ICRP recommendation that exposure of aircrew be treated as occupational exposure [I12], and the subsequent inclusion in both the IAEA [I5] and the European Union [E3] Basic Safety Standards.

B. RADON EXPOSURES IN WORKPLACES

244. The main source of exposure in most mining operations is radon. Since radon is also important in other workplaces, it is convenient to specifically consider exposure to it in the workplace. Exposure to long-lived radionuclides in mineral dusts can, however, be important in certain mining and other situations, and these will be discussed below.

245. Several isotopes of radon exist in nature, but one, ^{222}Rn, dominates in terms of the dose to workers. Under some circumstances, ^{220}Rn (commonly known as thoron because it is in the ^{232}Th decay chain) may also be important. For convenience, unless otherwise stated, radon is taken here to mean ^{222}Rn. The short-lived decay products, or progeny, of radon rather than the gas itself are the main cause of exposure, although for control purposes, it is often the concentration of the gas that is quoted. Workplaces themselves are often categorized as being either below ground or above ground. The main below-ground workplaces are mines, but there are also radon spas [S3], subways, show caves and tourist mines, and underground water treatment works and stores. Above-ground workplaces include factories, shops, offices, and schools. In the UNSCEAR 1993 Report [U3], only the exposure to radon progeny in underground mines was considered.

246. The levels of radon in workplaces are exceptionally variable, and high doses to workers can arise in places other than uranium mines. It is generally accepted that it would be unreasonable on the grounds of cost to consider controlling the normal ambient levels of radon in workplaces. These levels are therefore usually regarded as essentially unamenable to control. However, in recent years there has been increasing interest in those workplaces, including mines, where levels are high and there is some scope for reducing them. The approach adopted by ICRP [I12] is that the regulatory agency should identify the workplaces that warrant control. This necessitates surveys to determine the range of exposures, and it is clear that many countries have yet to complete such surveys and to determine where controls should be applied. The special quantities and units that are used to characterize the concentration of radon progeny in the workplace and the exposure of workers to them are discussed in Chapter I.

1. Underground mining

247. Mining is an extensive industry. In 1991, there were an estimated 4.7 million underground miners worldwide (see Table 30), about 84% of them engaged in coal mining and the remainder engaged in mining other minerals [C4]. In the latter group are about 90,000 persons engaged in the mining of uranium ores. China is the largest employer of workers in coal mines, and South Africa of workers in other mines (mainly gold mines). These numbers fluctuate from year to year with changing economic conditions. The exposure to radon progeny depends on a number of factors, including the type of mine, the geology, and the working conditions, particularly the ventilation. Available data from the UNSCEAR Survey of Occupational Radiation Exposures to miners are included in Table 29. Exposures to natural sources of radiation arising from mining have received much less attention than those arising from the industrial and medical uses of man-made sources of radiation. Relatively few data are available for the period of interest, and their quality or reliability is generally much lower than for the data reported elsewhere in this Annex for other occupations. This is a consequence of the paucity of the data as well as the fact that many were derived from environmental, as opposed to personal, dosimetry; dose estimates are subject to considerable error when they are based on grab samples of air instead of personal air samplers. This situation is changing, however, and more comprehensive and reliable data can be expected in the future.

248. In 1991, there were about 50,000 underground coal miners in the United Kingdom. In general, the exposure of coal miners to radon is low because good ventilation is required. The average effective dose to coal miners from radon was 0.6 mSv in that year, with about 70 miners receiving more than 5 mSv and 10 of them more than 15 mSv [H3]. The total collective dose from radon to coal miners was estimated to be 28.6 man Sv. A survey of non-coal mines (tin, gypsum, potash, etc.) that covered about 1,300 miners indicated an average annual effective dose of 4.5 mSv, with about 330 exceeding 5 mSv, of whom 240 exceeded 15 mSv and 3 exceeded 50 mSv [H3]. The total collective effective dose from radon to the non-coal miners in the United Kingdom was estimated to be about 6.1 man Sv.

249. The exposure of workers in South African gold mines is generally low, but the size of the workforce is substantial [W4]. In the mid-1990s, the annual production from 40 mines was about 100 Mt of ore and 600 t of gold. About 2,000 t of U_3O_8 is produced as a by-product from three of the mines. The average number of employees in the gold mines, including contractors, was about 310,000, about 250,000 of whom worked underground. The mean depth of the workings is 1,600 m, and the maximum is about 3,500 m. Such depths require a substantial throughput of cooled air to maintain an acceptable working environment, which is the reason why radon progeny concentrations are generally low. In surveys conducted between 1989 and 1991, it was found that 97% of the workers were exposed to less than 1,100 Bq m^{-3} (0.3 WL) and that no workers were exposed to more than 3,700 Bq m^{-3} (1 WL) [W3]. Since then, another survey was carried out in 1992 and 1993 in 21 of the mines; that survey covered 60% of the total underground workforce [W4]. The average concentration of nearly 2,000 measurements was 190 Bq m^{-3}, and 96.7% of the readings were below 1,100 Bq m^{-3}. The maximum was 3,300 Bq m^{-3}. Gamma dose rates and exposure to long-lived radionuclides in ore dusts were also measured. Effective doses from radon progeny were determined by both individual dosimetry and area measurements; the former gave values that were, on average, about 50% lower than the latter. Doses from radon progeny generally made the main contribution to total effective dose (on average, 1.8 mSv in a year, or 71%), with external gamma radiation representing the next largest component (0.64 mSv in a year, or 25%). Long-lived alpha radiation from ore dust contributes very little to the total effective dose (0.11 mSv in a year, 4%). On the assumption that the value for radon applies to all 40 gold mines, the annual collective effective dose in South African gold mines in the first half of the 1990s would have been 450 man Sv. The total annual collective effective dose from all three sources considered would have been 640 man Sv.

250. In Germany, an estimated 1,000 persons are employed in underground mines (other than uranium or coal mines) that expose them to radon levels between 1,000 and 3,000 Bq m^{-3} [S2]. A further 200 persons are employed in mines where the levels exceed 3,000 Bq m^{-3}. These mines include show caves and tourist mines. A few hundred workers in coal mines are estimated to be exposed to radon concentrations of 1,000–3,000 Bq m^{-3}.

251. The data taken from the UNSCEAR Survey of Occupational Radiation Exposures and reported in Table 29 are limited and on their own not sufficient to allow an estimate of worldwide exposure. Over the years, there have been a number of studies of doses to workers in underground mines; they are summarized in Table 31. The data, which are presented separately for coal mines and other mines (excluding uranium), cover some 1,200 mines. They refer to various time periods, which limits the extent to which they can be evaluated in a coherent manner. Neither the quality nor the extent of the data are considered adequate to allow their use to establish trends in worldwide exposures from underground mining. They have, however, been used to estimate worldwide doses from the inhalation of radon progeny; these are summarized in Table 32. The doses can be considered broadly representative for the early 1990s. They were estimated as the sum, over all the countries, of the products of the number of miners and the reported exposure to radon progeny. The average exposure for those countries reporting data has been assumed to apply worldwide.

252. The worldwide annual collective effective dose from the inhalation of radon progeny in underground mines (excluding uranium mining) is estimated to be about 3,200 man Sv, with about 1,400 man Sv (40%) arising from coal mines and about 1,800 man Sv (60%) from other mines. The comparable figures reported in the UNSCEAR 1993 Report [U3] for 1985–1989, were 5,300 man Sv overall and 1,500 and 3,800 man Sv for coal mining and other mining, respectively. The

drop for 1990–1994 is attributable to two main factors. First, the UNSCEAR 1993 Report [U3] used the ICRP recommended conversion factor of 1 WLM = 5 mSv [I13], as opposed to 1 WLM = 5.6 mSv, which had been used previously. Secondly and more importantly, for the non-coal-mine estimate, the most up-to-date data [W4] have been used for the South African miners. The South African data dominate the non-coal-mining data, and that for the early 1990s (average annual effective dose of 1.8 mSv) is significantly lower than the value of 5.6 mSv derived from data in the 1970s and used in the UNSCEAR 1993 Report [U3].

253. Exposures may also occur from external irradiation and from the inhalation of thoron progeny and of dust containing long-lived alpha emitters of the uranium and thorium series; consequently, the dose estimates in Table 32 from the inhalation of radon progeny alone understate the total dose. Few data are available on these other pathways of exposure, and their relative magnitudes will vary from mine to mine depending on the geology and working conditions. Estimates made for a number of mines in the former USSR [P3] suggest that the contribution from other pathways is about 1 mSv per year, which, except in coal mines, is a small fraction of the dose from radon progeny. This value was used in the UNSCEAR 1993 Report [U3]; however, the value available from the South African survey [W4] is 0.75 mSv. Overall it would seem appropriate to use a value of 0.8 mSv to account for the other pathways. When such an allowance is made, the annual collective effective dose from all exposure pathways for coal mining worldwide would become about 4,500 man Sv and that for other mining (excluding uranium) about 2,400 man Sv. The corresponding average annual effective doses from all pathways would be about 1.2 mSv and 3.2 mSv for coal and other mines, respectively.

254. The doses estimated in the above manner represent exposures received by miners at work in underground mines. They require further correction, however, if they are to be compared directly with exposures arising in other industries, where exposures from natural sources of radiation are not included in the reported doses. Similar correction is needed if the quantity of interest is the additional, rather than the total, dose received while at work. To facilitate fair comparisons with exposures in other industries and to allow the derivation of a quantity that represents the additional exposure from the work, the above annual dose estimates need to be reduced by about 0.5 mSv; this is the annual dose that the worker would otherwise have received if not at work. It is based on 2,000 hours work per year and a worldwide average dose from external irradiation and inhalation of radon progeny of 2.4 mSv (see Annex B, "*Exposures from natural radiation sources*").

255. After correcting for other exposure pathways and for exposures that would have been received irrespective of work, the worldwide annual collective effective dose from underground (non-uranium) mining during the early half of the 1990s is estimated to have been about 4,600 man Sv; about 2,600 man Sv arose in coal mining and 2,000 man Sv arose in other mines (excluding uranium). Of those countries identified separately in Table 32, South Africa (about 39%) makes the largest contribution to the total collective dose, with significant contributions also coming from the former USSR (about 19%) and Poland (about 22%). The additional worldwide average annual effective dose received by underground miners from their work is estimated to have been about 0.7 mSv in coal mines and about 2.7 mSv in other mines (excluding uranium), although there was considerable variation about these averages from country to country and from mine to mine in a given country. Somewhat greater individual and collective doses are likely to have been received in the late 1970s and early 1980s because less attention was paid to the control and reduction of exposures from this source. Insufficient data are available, however, to allow reliably estimating how much greater they might have been; the few data in Table 31 suggest that they may have been substantially greater.

256. Very approximate and tentative estimates were made in the UNSCEAR 1988 Report [U4] of collective doses from natural sources of radiation. For coal mining, an upper estimate of 2,000 man Sv was made for the worldwide annual collective effective dose; this was based solely on exposures in mines in the United Kingdom and on the worldwide production of coal. Given its very approximate nature and the change adopted here in the conversion factor for exposure to radon progeny, the estimate compares favourably with the current estimate of about 2,600 man Sv. A very rough estimate of 20,000 man Sv was also made in the UNSCEAR 1988 Report [U4] for the annual collective effective dose from underground mining apart from coal and uranium; that estimate was based on a very tentative assumption that the arithmetic mean annual individual dose was 10 mSv (from a range of reported values between 0.1 and 200 mSv) and that there were, on average, 500 underground miners (excluding coal and uranium) per million population. This earlier tentative estimate was revised downward to 4,100 man Sv in the UNSCEAR 1993 Report [U3] on the basis of better data. Further improvements in data and changes in the conversion coefficients have allowed a lower estimate for non-coal mines (other than uranium): 2,000 man Sv. The overall estimate for underground mining, 4,600 man Sv, is about two thirds of that for the period 1985–1989.

2. Exposures above ground

257. Exposures to radon progeny may be important in some above-ground workplaces. Radon exposures are largely determined by the geology underlying the building, its construction, and the ventilation. It has been known for some time that high levels of radon exist in some dwellings, but it is only relatively recently that attention has been paid to workplaces other than mines. The spectrum of places where radon can present a hazard is potentially large and includes shops, schools, and offices. Radon entry into buildings is from both diffusion and pressure-driven flow of soil gas through cracks in the floor. The mechanisms of radon entry into buildings are discussed in Annex B, "*Exposures from natural*

radiation sources". Building materials and radon in water may also contribute to the levels of radon in buildings. The experience obtained from studies of radon levels in dwellings may help to identify those workplaces where radon concentrations may exceed any action level specified by the national authority for the purpose of determining whether controls need to be applied. Some countries have used the concept of radon-prone areas, as suggested by ICRP [I13]. These areas can be defined in a number of ways. One way is to define them as areas in which at least 1% of the dwellings have radon levels more than 10 times the national average.

258. In Germany, the number of persons exposed to radon concentrations between 1,000 and 3,000 Bq m^{-3} was estimated to be about 50,000 [S2]. A further 10,000 were estimated to be exposed to a radon concentration of more than 3,000 Bq m^{-3}. These are only crude estimates. Another 2,000 or so persons in working places associated with the water supply industry were estimated to be exposed to radon concentrations between 1,000 and 3,000 Bq m^{-3} and about 300 persons to levels above 3,000 Bq m^{-3}. Elevated levels of radon in above-ground workplaces have been found in a number of countries. Levels above 1,000 Bq m^{-3}, the action level suggested in the international basic safety standards [I5], have been found in some countries, but often the sample sizes were small. In the United Kingdom, radon concentrations were measured in 4,800 workplaces in areas of the country where levels were expected to be above average. The mean concentration was 210 Bq m^{-3}, and in 710 cases the concentration exceeded 400 Bq m^{-3}. Of the estimated 1.7 million workplaces in the United Kingdom, 5,000 workplaces with about 50,000 workers are expected to exceed this level [H3]. Their collective effective doses and average individual doses are 270 man Sv and 5.3 mSv in a year, respectively, with 2,500 or so workers receiving doses exceeding 15 mSv in a year.

259. There are clearly very few data on which to base an estimate of worldwide exposure. However, a crude estimate could be based on the United Kingdom experience. As with underground mining it is necessary to make an adjustment for the general ambient level of exposure to radon. If the same reduction is used, the estimated average annual collective dose to those exposed above the action level would drop to about 240 man Sv in the United Kingdom. If this figure is then extrapolated on the basis of GDP, the worldwide annual collective effective dose would be about 6,000 man Sv. This is clearly very crude, and country-to-country variables such as geology, building materials, configurations, and regulations could have a significant effect. This is an area where more data are needed to help refine the estimates.

C. EXPOSURES IN MINERAL PROCESSING INDUSTRIES

260. The earth's crust generally contains concentrations of uranium of the order of 0.5–5 ppm and of thorium of the order of 2–20 ppm. The average activity concentration of ^{238}U and ^{232}Th are in the range 25–50 Bq kg^{-1} (see Annex B, "*Exposures from natural radiation sources*"). However, both elements may be concentrated in certain rocks by geological processes such as partial melting and recrystallization, which can be caused by the movement of tectonic plates and other processes. Uranium and thorium are sometimes enriched in granites and alkaline igneous rocks, often accompanied by tin and minerals containing rare earth elements. Particularly high concentrations can occur in coarsely crystalline rocks called pegmatites, which are formed during the solidification of the last fraction of molten rock, where relatively high concentrations of less common elements have built up. Uranium is also concentrated in some conglomerates, sandstones, black shales, and phosphorites by sedimentary processes. These sedimentary uranium materials may be mobilized and the uranium concentrated by metamorphic processes to form complex deposits that usually contain ores of many metals. Uranium not only occurs in minerals such as pitchblende (uraninite) but also, like thorium, may be enriched in various hard and resistant materials such as zircon and monazite. Weathering, wave action, and similar mechanisms may concentrate such materials into heavy mineral sands, such as the monazite sands of Brazil, southern India, and Western Australia.

261. There is a substantial worldwide industry in which materials with relatively high concentrations of uranium and thorium are mined and milled, either for the sake of the metals themselves or for the other materials that occur with them, such as the rare earths and phosphates. In addition, during the processing of some materials, concentrations of natural radionuclides, often out of secular equilibrium with their parents or daughters, may build up in scales and in other (usually waste) materials. This can happen in ore smelters, in plants that process calcium phosphate in the production of phosphoric acid and fertilizers, and in the pipes and valves on oil platforms and in refining facilities. Some of these minerals and materials are known to have the potential to cause significant occupational exposure; they are listed in Table 33 [E2, N4]. The listing is incomplete simply because the materials have not come under regulatory control and have not, as a result, been fully studied. The data in the table should therefore be regarded as illustrative rather than exhaustive. Uranium ore could have been included here but is instead considered in Chapter II, along with other sources of exposure arising in the nuclear fuel cycle.

262. The mining and milling of ores with elevated levels of natural radionuclides and their subsequent processing can lead to the exposure of personnel from external radiation and from intake, primarily inhalation [D2]. Exposure to dusts is particularly important during dry operations with bulk material in enclosed facilities. Exposures can also come from the scales that build up in the plant. During normal operations, this is likely to be largely due to external radiation; internal exposure may, however, arise during maintenance and cleaning operations. Exposure to radon needs to be taken into account, but as identified in Section V.B this route of exposure is not solely dependent on the activity concentrations of the material being handled.

263. For the purpose of determining when radiological precautions may be required in handling materials with elevated levels of natural radionuclides, some assessments of dose have been undertaken [D2, I17]. Under somewhat pessimistic assumptions, materials containing activity concentrations of between 1 and 10 kBq kg^{-1} of parent radionuclide could result in annual effective doses to workers of the order of 1 or 2 mSv from external and internal exposure. The assumptions used in the assessment of internal exposure were airborne dust concentrations of 5 mg m^{-3}, continuous occupational exposure conditions and no respiratory protection, 5 μm activity median aerodynamic diameter (AMAD), and the new ICRP dosimetry [I17]. An evaluation of the available literature has shown that handling substances containing natural radionuclides with an activity concentration of less than 1 Bq g^{-1} of the parent radionuclide generally leads to effective doses of less than 1 mSv in a year, even in the most unfavourable circumstances [S2].

264. There is a particular interest in the occupational exposures associated with mineral sands, which contain significant concentrations of thorium (up to 8%). These are mined and processed in several countries for their thorium content, although more typically for the other materials such as rare earths and rutile. Typical concentrations of thorium and uranium in commercially important minerals from Western Australia are given in Table 34. It can be seen that the industry is primarily concerned with the production of ilmenite. Monazite, however, is important because of its relatively high thorium content and its propensity to concentrate preferentially in airborne dust in the separation plant by a factor of between 10 and 30 [H4, H6, H7, J1, K1].

265. Sand mined from a suitable site undergoes a preliminary separation stage at the mine that removes approximately 90% of the light quartz minerals [J1]. The remaining heavy minerals are transported to a sand-processing plant, where further separation and concentration produces the four main commercial sand fractions: ilmenite, rutile, zircon, and monazite. Both wet and dry separation techniques are used. In Australia, measurements in one processing plant and its environs gave an average dose rate of 0.4 μSv h^{-1} [J1]. Levels close to a stockpile of monazite were reported to be up to 1.5 μSv h^{-1}. Even higher levels from monazite have been reported elsewhere: external exposure levels ranging from less than 10 μGy h^{-1} to more than 100 μGy h^{-1} in storage areas [I9, K1]. Over a working year, the exposure levels in the Australian plant were estimated to give an effective dose of 1 ± 0.5 mSv. Internal exposure has been of greatest concern, however, owing to the use of dry processing techniques and the dustiness of the operations. In the same plant, airborne dust concentrations averaged 3.3 ± 2 mg m^{-3}, with an average AMAD of 3.2 μm (GSD: 2.8); using previous ICRP dosimetry, this gives an average annual effective dose of 7 mSv [J1]. In Western Australia, around 1,500 workers are involved in the mining and processing of the heavy mineral sands and a further 500 are employed in various downstream processing activities, but only 150–200 employees are designated as radiation workers. Workers are so designated on the basis of their potential to receive an annual effective dose in excess of 5 mSv. Typically, only workers involved in the operation and maintenance of the dry separation plants would be designated as radiation workers [H4, H6, H7]. One downstream process is the practice of manufacturing gas mantles containing thorium. This is known to be widespread in many countries, however, no data were provided and no estimate has been made of the resulting occupational exposure.

266. The trends in the maximum and mean annual effective doses to designated workers over a 10-year period, 1986–1995, in the Western Australian mineral sands industry are shown in Figure XIII [H4]. Significant reductions have been achieved, the mean annual dose having declined from just under 25 mSv (90% external, 10% internal) to around 6 mSv (85% external, 15% internal) in 1990–1994. It is estimated that exposures before 1986 were higher than those shown; in plants that operated in the late 1970s and early 1980s and that produced large quantities of monazite, exposures could have been twice as high. The annual external exposures to monazite plant operators and monazite product baggers regularly exceeded 10 mSv in the 1970s [H4, H6, H7]. Most of the decline has been in the internal dose. The annual external radiation dose has remained relatively constant over the 10-year period, being in the range 1–2 mSv. In the UNSCEAR 1993 Report [U3], the average annual effective dose to 376 dry-process workers was reported to be 20 mSv for 1983–1988, with 50% of the workers above 15 mSv. About 90% of the dose for this period came from internal exposure. Further substantive reductions in airborne concentrations are considered unlikely in the absence of a fundamental change in the processing technology. The above-quoted internal exposures should be reduced by a factor of 3 to be consistent with ICRP Publication 68 [I15].

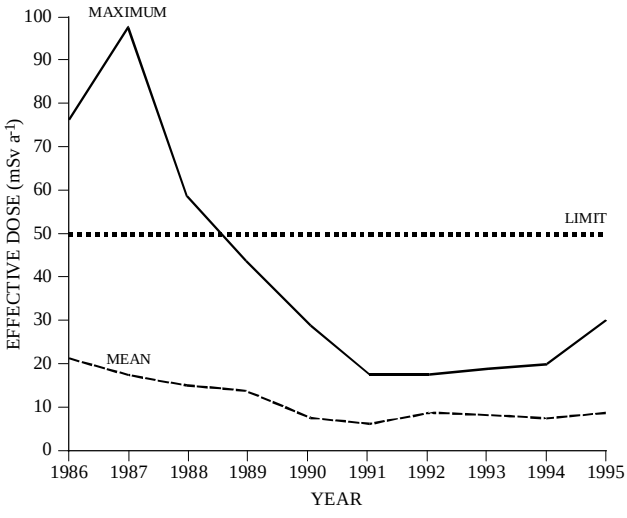

Figure XIII. Trends in effective doses to workers in the mineral sands industry in Western Austrlia [H4].

267. There have been proposals for the processing of monazite to produce rare earth metals, and a plant is likely to be built in Australia in the near future. In this plant, the monazite grain will be cracked open and the radionuclides solubilized in the process. This plant will require high standards of

occupational protection. Similarly, there have been demands for the uranium and thorium content of mineral sand products to be reduced. To do this will require chemical separation, and high standards of occupational protection will again be required [H4, H6, H7].

268. Countries other than Australia where mineral sands are mined include India, Malaysia, and South Africa. Several thousand workers in each of these countries are involved in the mining and milling of the sands. About 600 workers in China and 300 workers in the United States are involved in bastnaesite mining (a rare earth mineral also containing significant amounts of thorium) [I9]. It is also perhaps worth noting that workers in plants where the products from the processing of mineral sands are used may also receive significant exposures if precautions are not taken. For example, assessments of dose have been reported for one factory in Italy handling zircon sand for producing refractory materials [B2]. The sand had activity concentration of ^{238}U of about 3 kBq kg^{-1} and an activity concentration of ^{232}Th of about 0.8 kBq kg^{-1}. Owing to the large particle size of the material, there was effectively no inhalation hazard associated with the untreated material; the doses from external radiation were generally low, being unlikely to exceed 1 mSv in a year. However, where the material was heated and ground, annual effective doses of 5 mSv could be received (based on the old ICRP dosimetry). There was some evidence that the airborne dust was enriched in ^{210}Po.

269. Uranium and thorium are associated with phosphatic deposits of marine origin. They occur in beds of varying depths; in Florida, they occur in deposits with up to 15 m of overburden. Concentrations of ^{238}U at the surface are typically of the order of 20–40 Bq kg^{-1} and increase gradually with depth to values of the order of 700–4,000 Bq kg^{-1} immediately above or in the matrix [N4]. In mining and beneficiation, gamma radiation levels range from normal to 50–100 nGy h^{-1} over unmined land and up to 1 μGy h^{-1} near large quantities of beneficiated rock. This is not an important route of exposure, however, since annual effective doses from external radiation do not exceed 1 mSv above normal background.

270. Where the rock is handled in the dry state, there is the potential for airborne dusts, and control measures may be needed. In phosphoric acid plants, elevated gamma radiation levels have been found in some Florida facilities, with calculated values up to 0.4 mSv in a week [N4]. The greatest potential for exposure has been found to be in filter pan refurbishing, either at the plant or at off-site machine shops. External gamma radiation levels in filter pan cleaning and maintenance range from 10 μGy h^{-1} in the general vicinity to 120 μGy h^{-1} in contact with the uncleaned pan. Cumulative doses to workers would depend on a number of factors but clearly could exceed 1 mSv in a year.

271. The production processes in oil and gas extraction industries do not routinely involve the widespread dispersal of activity into the working environment, as does the handling of bulk quantities of materials. They can, however, lead to quite substantial deposits of activity in some plants. Furthermore, the physical and chemical reactions during processing can alter the state of equilibrium of the radionuclides such that individual radionuclides may become concentrated to levels many times their level in the source material. The radionuclide of principal concern for occupational exposure is ^{226}Ra (and ^{228}Ra), which accumulates in scale that must periodically be removed [H5]. The conditions and chemical composition in the well fluids and process streams vary considerably, depending on operational factors such as the characteristics and numbers of producing wells and the extent of water injection. It is also likely that the concentrations of radium-bearing compounds underground will vary between and within fields. The location and extent of scale accumulation depend on such factors as the turbulence of flow, temperature, and acidity. The consensus is that most deposition is from the aqueous phase, so the presence of water in a process stream or vessel can signal the potential for scale deposition. In oil wells in the United Kingdom, scales commonly have an activity concentration of 1–10 Bq g^{-1} but can be an order of magnitude higher [D3]. Levels as high as several kilobecquerels per gram have been reported [H5].

272. An indication of the number of workers involved in handling materials containing elevated levels of natural radionuclides is available from Germany [S2]. The number of workers involved with phosphate fertilizers who receive between 1 and 6 mSv in a year is estimated to be 1,000 in the trade (e.g. store workers) and 2,000 in the application of the material (in farming). The activity concentration of the material is above 2 Bq g^{-1} of uranium and its progeny. It was estimated that about 100 workers involved with zircon sands (activity concentration of 5–10 Bq g^{-1} of thorium decay chain radionuclides) and 30 involved with pyrrhite ore (activity concentration of natural radionuclides up to 30 Bq g^{-1}), and 10 with copper slag processing receive similar doses.

273. While a number of specific studies have been noted above, the information is fragmented and covers a wide variety of situations. It is clear that some of the operations in the mineral processing industries provide the potential for significant exposure and, as shown by the data in Figure XIII, can cause average individual doses to exceed the dose limit. These high dose situations arise largely from the potential for exposure not to be recognized and hence not to be brought under regulatory control, rather than from poor application of protection standards. This potential is driving efforts to bring such situations within a regulatory framework [E3, I5], and hopefully more coherent data will be available for future reviews. Despite the high doses noted above, the examples presented support the supposition in the UNSCEAR 1993 Report [U3] that the average annual dose to workers is unlikely to exceed 1.0 mSv. That Report made a crude estimate of some 200 man Sv from this practice, then folded in an estimate of exposure arising from coal-fired power plants of the order of 60 man Sv, and concluded that a global figure of 300 man Sv would be appropriate. Again, in the absence of firm evidence, the crude estimate of average annual collective dose worldwide of 300 man Sv is considered the best available estimate.

D. SUMMARY

274. A common feature of the estimates of exposure to natural radiation from various practices is the very limited amount of data on which the estimates are based and the high uncertainty. These estimates, summarized in Table 35, should therefore be treated with caution. The overall collective dose is very significant; some 11,700 man Sv. The main contributors are, firstly, mining (2,600 man Sv from coal mining and 2,000 man Sv from other mining) and, secondly, the above-ground (in buildings) inhalation of radon and its decay products, some 6,000 man Sv. This latter figure in particular should be regarded as a crude estimate. It is hoped that better data will be available for future assessments.

VI. DEFENCE ACTIVITIES

275. Radiation exposures to workers in defence activities can be grouped into three broad categories: those arising from the production and testing of nuclear weapons and associated activities; those arising from the use of nuclear energy as a source of propulsion for naval vessels; and those arising from the use of ionizing radiation for the same wide range of purposes for which it is used in civilian spheres (e.g. research, transport, and non-destructive testing). Previous UNSCEAR reports reviewed the first two of these activities separately. While this approach is continued here, it must be recognized that there is a degree of overlap between the categories and also that the limited number of countries responding to the UNSCEAR Survey of Occupational Radiation Exposures constrains the conclusions that can be drawn. The third broad category, that of exposure from conventional industrial, medical and research uses, has not been separately identified in the data provided and is therefore not addressed further here, but it may be a consideration for future reviews.

A. NUCLEAR WEAPONS

276. Nuclear weapons have been developed, tested, and deployed by five countries: China, France, the former USSR, the United Kingdom, and the United States. The main potential sources of occupational exposure in the development and production of nuclear weapons are the two radioactive fissile materials plutonium and uranium and tritium. Exposures may arise by two main routes: (a) the intake of these materials into the body by inhalation or ingestion (or absorption through the skin in the case of tritium) and (b) external irradiation from gamma rays and, to a lesser extent, neutrons. Intake of these elements into the body is minimized by avoiding direct contact and providing containment for the materials during their fabrication into weapons. Some small intakes will, however, inevitably occur, and monitoring is generally undertaken to determine their magnitude. The nature and extent of monitoring depend on the potential for exposure. Where material is being processed, the monitoring may include the use of personal air samplers, whole-body monitoring, and bioassay; where the potential for intake is much less, area monitoring of airborne levels may suffice. Because of the steps taken to provide confinement for these materials, external irradiation tends to be the dominant source of exposure for those involved in the production, testing, and subsequent handling of nuclear weapons. As the energy of the gamma radiation typically emitted by the more common isotopes of these elements is relatively low, this is one area where the direct recording of the dosimeter measurement as the received whole-body or effective dose, as is common practice, could lead to significant overestimates. Neutron as well as gamma dosimeters may be used where exposures from the former may be significant.

277. In the United States, the Department of Energy (DOE) is responsible for stewardship of the nuclear weapons stockpile and the associated facilities, for restoring the environment at related sites, and for energy research [D4]. The facilities covered include accelerators, fuel/uranium enrichment, fuel fabrication, fuel processing, maintenance and support, reactor operation, research, waste management, weapons fabrication, and testing. The annual numbers of workers involved in these activities, including the number monitored and the number with measurable doses during 1990–1994, are given in Table 36. In the United Kingdom, the Atomic Weapons Establishment is the organization whose stewardship is comparable to that of the United States Department of Energy. Relevant data are given in Table 37. During the time periods covered by the four previous UNSCEAR reports, the United Kingdom and United States were the only countries that provided substantive data (these can be seen in the first part of Table 38). Included in the table are all employees, contractors, subcontractors, and visitors. Also indicated are the collective doses, in total and by component of exposure. It should be noted that between 1992 and 1993, the United States changed its method of calculating internal exposure, with the result that doses before and after these years are not directly comparable. The changes in reporting requirements had a significant impact on the collective dose over this period. The collective dose seemed to decrease by up to 28% because the dose from intakes in previous years is no longer reported in the current year.

278. In the United States the data averaged over five-year periods given in Table 38 indicate that the number of monitored workers has risen from 15,900 in 1985–1989 to 20,800 in 1990–1994. However, the most important difference is a halving of the annual collective effective dose between these two periods from 11.9 to 5.9 man Sv. A number of factors are relevant here. First, the operational status of many of the DOE facilities has changed, with many having been shut down and having gone through transition

from operation to stabilization or decommissioning. Production of plutonium at the Hanford Site ceased in 1990. In 1989, the plutonium fabrication plant at the Rocky Flats site was shut down for safety code violations, and many production functions were suspended. Plutonium operations were halted at the Rocky Flats site in 1991. By 1988, no DOE reactor was producing tritium for nuclear weapons. By 1992, the United States was no longer building nuclear weapons. This programme appears to have involved many contractors. The second relevant point is the policy on who is included in monitored workers. For 1990–1994, they included all DOE employees, contractors, subcontractors, and visitors. The Department of Energy notes [D8] that the number of monitored workers may not be indicative of the size of the exposed workforce because some establishments provided dosimetry to individuals for reasons other than radiation protection, e.g. for reasons of security, administrative convenience, and legal liability. As a result, it may not be valid to compare the size of the monitored workforce over time. Similarly, such a large monitored population can confound comparisons of dose. The average annual dose to monitored workers thus appears to have decreased by a factor of three between the last two periods, which is somewhat more than the decrease in the average annual collective dose.

279. The number of monitored workers in the United Kingdom has stayed roughly constant, around 4,000. The average annual collective effective dose after an initial increase from 2.0 to 3.6 man Sv over the first two periods subsequently decreased by a factor of 3, to 1.2 man Sv for 1990–1994. A similar pattern is seen with the average annual dose to monitored workers, which over the four periods decreased from 0.94 to 0.28 mSv.

B. NUCLEAR-POWERED SHIPS AND THEIR SUPPORT FACILITIES

280. Nuclear-powered ships (submarines and surface vessels) are operated by several navies, in particular those of China, France, India, the former USSR, the United Kingdom, and the United States. Pressurized water-cooled reactors are the power source in almost all cases; in the former USSR several reactors are cooled by liquid metal. Radiation exposures arise on board ship and also at shore-based support facilities, where maintenance, refuelling, etc. are carried out and personnel are trained.

281. Data on occupational exposure from nuclear-powered ships and support activities in the United Kingdom for 1990–1994 are given in Table 37 on a year-by-year basis and summarized as an entry in Table 38. The data [H3, H9] stem from the Defence Radiological Protection Service (DRPS); while they cover naval activities, the data also cover components from the other armed forces and many of the industrial-style practices used by them. There may therefore be some differences between the workforces reported on for 1990–1994 and those reported on previously. However, these differences probably do not distort the data significantly. The number of monitored workers, about 6,300, was reasonably constant for the first three periods but in 1990–1994 increased to about 9,800. Despite this increase, the average annual collective effective dose dropped from 11.6 man Sv for 1985–1989 to 8.0 man Sv for 1990–1994. This continues the downward trend from 26.3 man Sv in the first period. In previous periods the total reported data were dominated by United States data, but that country did not contribute data on nuclear-powered ships for the UNSCEAR Survey of Occupational Radiation Exposures.

C. SUMMARY

282. Data on occupational exposure from all defence activities are summarized in Table 38. Although this period has seen the introduction of data from France and the Netherlands, the bulk of the data still comes from just the United Kingdom and the United States, with the latter dominating. The total number of monitored workers averaged over five-year periods has increased steadily, from about 100,000 in the first period to 140,000 in 1990–1994. The average annual collective effective dose fell from about 140 man Sv in the first period to about 80 man Sv in the second and third periods, with a significant further reduction to 33 man Sv for 1990–1994. The average annual effective dose to monitored workers decreased in each period from 1.3 mSv in the first period to 0.24 mSv for the most recent period. Given the much larger contribution made by the United States to the overall data, these parameters mainly reflect the experience in that country. Here attention is drawn to the comments made in Section VI.A, concerning nuclear weapons, and the different data coverage in the different periods.

283. The above data need qualifying with regard to their completeness, in particular to whether they include all significant occupational exposures associated with defence activities. For example, they do not include occupational exposures incurred in the mining of uranium used in either the nuclear weapons or the nuclear naval programmes; nor is it clear to what extent the reported data include exposures arising during the enrichment of uranium for both the weapons and naval programmes or exposures arising in the chemical separation and subsequent treatment of plutonium. Such omissions, should they exist, are significant only in the context of proper assignment of exposures to different practices; any omission here is likely to be compensated for by an overestimate of exposures in other practices (e.g. exposures in mining, enrichment, and fuel reprocessing attributed to the commercial nuclear fuel cycle).

284. The data presented above for all defence activities include occupational exposures for three countries that have developed and deployed nuclear weapons or that operated nuclear ships, namely, France, the United Kingdom, and the United States. Any estimate of worldwide occupational exposures from defence activities can, therefore, be made only by extrapolating the available data. Inevitably, this can only be done very approximately, and neither method of extrapolation presented in Section I.E is appropriate.

285. The UNSCEAR 1993 Report [U3] reviewed the potential for extrapolation based on normalized collective dose, with the normalization performed in terms of unit explosive yield for weapons and per ship or installed nuclear capacity for the naval propulsion programme. It concluded that such extrapolation was not viable. Pending the acquisition of further data, the UNSCEAR 1993 Report [U3] proposed adopting a very simple approach for estimating worldwide exposures from this source, namely, that the worldwide collective dose from defence activities is greater by a factor of 3 than the sum of that experienced in the United Kingdom and the United States. Four assumptions underlay the choice of this factor: first, the level of defence activities in the former Soviet Union and the United States were broadly comparable; secondly, the levels of exposure in the former Soviet Union were greater than in the United States by an indeterminate amount that did not exceed a factor of 2 in 1975–1989; thirdly, the levels of exposure in France have been comparable with those in the United Kingdom; and, fourthly, the exposures in China were not as large as those in the former Soviet Union or in the United States. The addition in the most recent five-year period of the French data does not significantly change matters, and it is concluded that the above simple approach is still the best available in the circumstances. Based on these assumptions, the estimated worldwide average annual collective effective dose from defence activities would have been about 400 man Sv in 1975–1979, falling to about 250 man Sv in 1985–1989, and 100 man Sv in 1990–1994. Given the coarseness of the underlying assumptions, it is not be possible to give a precise estimate of the collective dose; perhaps all that can be concluded is that the worldwide average annual collective dose during the period analysed was about 100 to 300 man Sv. This estimate is inevitably associated with much uncertainty, which can only be reduced by relevant data from China and the former Soviet Union.

VII. MISCELLANEOUS OCCUPATIONAL CATEGORIES

A. EDUCATIONAL ESTABLISHMENTS

286. Research workers in educational establishments use radioactive sources, x-ray equipment, and unsealed radioactive sources for a wide range of activities. Examples of uses include x-ray crystallography, radioactive labels (e.g. ^{3}H, ^{14}C, ^{32}P, ^{35}S, and ^{125}I), and irradiators using ^{60}Co or ^{137}Cs sealed sources. In the UNSCEAR 1993 Report [U3], it was noted that the lack of consistency in reporting data made it difficult to estimate the level of exposure and to draw useful comparisons for this category of exposure. Data that should be rightfully attributed to this category are often attributed to other broad practices of radiation, such as research in the nuclear fuel cycle or industrial uses, and vice versa. The intent here is to include exposures arising in tertiary educational establishments (universities, polytechnics, and research institutes with an important educational role). Exposures from research related to the nuclear fuel cycle and from such activities as the use of accelerators should have been included in those more specific occupational categories.

287. The data reported by countries are given in the first part of Table 39. Worldwide levels of exposures have been estimated from national data by extrapolation within regions based on GDP. The coverage and scaling of data (by a factor of about 2.5) were similar to the coverage and scaling for industrial radiography. The collective effective dose is less well correlated with GDP than that for the other occupational categories analysed; the greater potential for non-uniform reporting of data in this category has doubtless contributed to this situation.

288. In the three previous periods the estimated worldwide number of monitored workers varied between 140,000 and 180,000, while the most recent period has seen an increase to 310,000, with the principal contributions coming from Canada, Germany, and Japan. This apparent doubling may be an overestimate attributable to the factors identified above. The average annual collective effective dose fell from 74 to 22 man Sv over the first three periods then rose to 33 man Sv for 1990–1994. Again, this might be a slight overestimate, but it is probably of the correct order of magnitude. The data show the average annual effective dose decreasing throughout all four periods, from 0.55 to 0.11 mSv. Although there is some variation from country to country, the dose profile data indicate few workers in this sector receive any significant doses. In line with this, the value for the average annual effective dose to measurably exposed workers, 1.1 mSv, is relatively small.

B. VETERINARY MEDICINE

289. Diagnostic radiography is the main source of occupational exposure in veterinary practice. In general, effective doses to individuals should be low, because they arise essentially from scattered radiation. Poor practice may, however, result in the unnecessary exposure of extremities if, for example, assistants hold animals in position while the radiograph is being taken. The data from the UNSCEAR Survey of Occupational Radiation Exposures are given in the second part of Table 39. The countries reporting for 1990–1994 are broadly the same as in the preceding period, with one critical exception: there are no data from the United States. In 1985–1989, the United States accounted for 85,000 of the reported 96,000 monitored workers and for 36 man Sv of the 37 man Sv total for collective dose. It is therefore difficult to meaningfully compare the different periods. However, if the United States data are removed from the reported data for the previous period (1985–1989) a

comparison of sorts can be made. The number of monitored workers in each period was about 11,000. Similarly, the average annual collective effective dose was just over 1 man Sv in each period and the average annual effective doses were about 0.1 mSv in each period. There are considerable variations between and within countries over the four time periods considered. Interpretation of this data needs to take into account many of the cautionary comments made for medical diagnostic exposure, particularly in regard to the large differences that can occur depending on whether dosimeters are worn above or below any protective lead aprons.

290. The vast majority of the data for 1990–1994 comes from OECD countries. The limited data set make it difficult to interpolate and produce a world estimate. If the procedure described in Section I.E is used, a worldwide collective effective dose of 8 man Sv results. This is not considered reliable enough to give anything other than a lower bound to the possible values. The estimate for the previous period, 52 man Sv, is probably more robust, and in the absence of better data a rounded figure of 50 man Sv could be assumed.

C. OTHER OCCUPATIONAL GROUPS

291. The "other occupational groups" category was included in the UNSCEAR Survey of Occupational Radiation Exposures to ensure that no sizeable group of exposed persons was overlooked. The data provided are given in the last part of Table 39; they cover disparate groups that often cut across the other categories reported on. In total, this category covers only an average annual number of monitored workers of some 9,000, receiving an annual average collective effective dose of 9.6 man Sv and an average annual effective dose of about 1.0 mSv. It is concluded that no significant group has been missed in the UNSCEAR Survey of Occupational Radiation Exposures.

D. ACCIDENTS WITH SERIOUS EFFECTS

292. Accidents that occur in the course of work add to occupational exposures and in some cases can have serious consequences. Accidents with clinical consequences for those exposed that occurred in 1975–1994 are listed in Table 40. The incidents are separated into accidents occurring in four activities: the nuclear fuel cycle and associated research, industrial uses of radiation, tertiary education and research (including accelerators), and medical uses of radiation. Most of the data were obtained in response to the UNSCEAR Survey of Occupational Radiation Exposures. Some additional entries have been made from other compilations of accidents [I22, R5] to the extent that dose information was available or clinical consequences could be ascertained. The data are shown in graphic form in Figure XIV. There are 11 accidents listed for 1990–1994 involving 27 significantly exposed persons, 4 of whom died. The 3 fatal accidents (one each in Belarus, China and Israel) were all related to irradiation facilities; they are covered in more detail below. These fatalities are in addition to the three fatalities previously reported for irradiators (in Italy, Norway, and San Salvador [I23]). Also noted below is the death of an industrial radiographer in the United Kingdom linked to chronic high-dose exposure [L2]. With the obvious exception of Chernobyl, it is the accidents in industrial uses that dominate the data reported to UNSCEAR. Over all four periods, and excluding Chernobyl, there have been 98 reported accidents with 144 workers significantly exposed (including 8 fatalities). Some 65% of the accidents and exposed persons have been in the industrial sector, with 7 out of the 8 fatalities also being in this sector. However, it should be noted that overall (and in the categories as well) there has been a general downward trend: the number of accidents reported in the first period was 40 and the number in 1990–1994 was 11.

293. The accidental exposures listed in Table 40 are those that occurred in the course of work. This reflects the approach taken in previous UNSCEAR reports, namely to exclude two categories of accident: exposures from the theft or loss of industrial or medical sources and the accidental exposure of patients during diagnosis or therapy. The exclusion of the first of these paints a less-than-complete picture, and there are grey areas in categorizing accidents. The most obvious example is that of workers in the metals recycling industries. While these workers are not direct users, lost or abandoned sources are entering the metals recycling industry with increasing frequency [C5, D5, L6], giving rise to health and economic consequences. Indeed the problem is serious enough for the industry to be investing heavily in installed systems to check incoming scrap metal for radioactive content. It could thus be argued that occupational exposure to radiation occurs in this industry. Table 41 lists accidents that have had significant consequences and may be of relevance but do not fall within the strict definitions of occupational exposure or the time frame that is the primary focus of this Annex.

294. The Committee previously noted that because accidents were likely to have been under-reported, conclusions could not easily be drawn on trends in the number and types of accidents that were occurring. While under-reporting still exists, in recent years there has been a serious attempt by IAEA [I4, I6, I7, I8] to study the detailed causes of some of the more serious accidents with a view to learning lessons that might be applied to future operations of a similar nature. There has been much interest in industrial irradiators, in which a number of fatal accidents have occurred. Such accidents inevitably arouse considerable interest, and it is likely that the information now available is reasonably complete. The degree of under-reporting of non-fatal accidents with clinical consequences is, however, still unclear. The information on the accidents in irradiator facilities given here comes largely from published reports, particularly a recent IAEA review of the lessons from industrial irradiator accidents [I8]. Industrial radiography is another area where accidents with clinical effects continue to occur. Once again, most of the information comes from published reports [L3, L4], but undoubtedly it is far from complete.

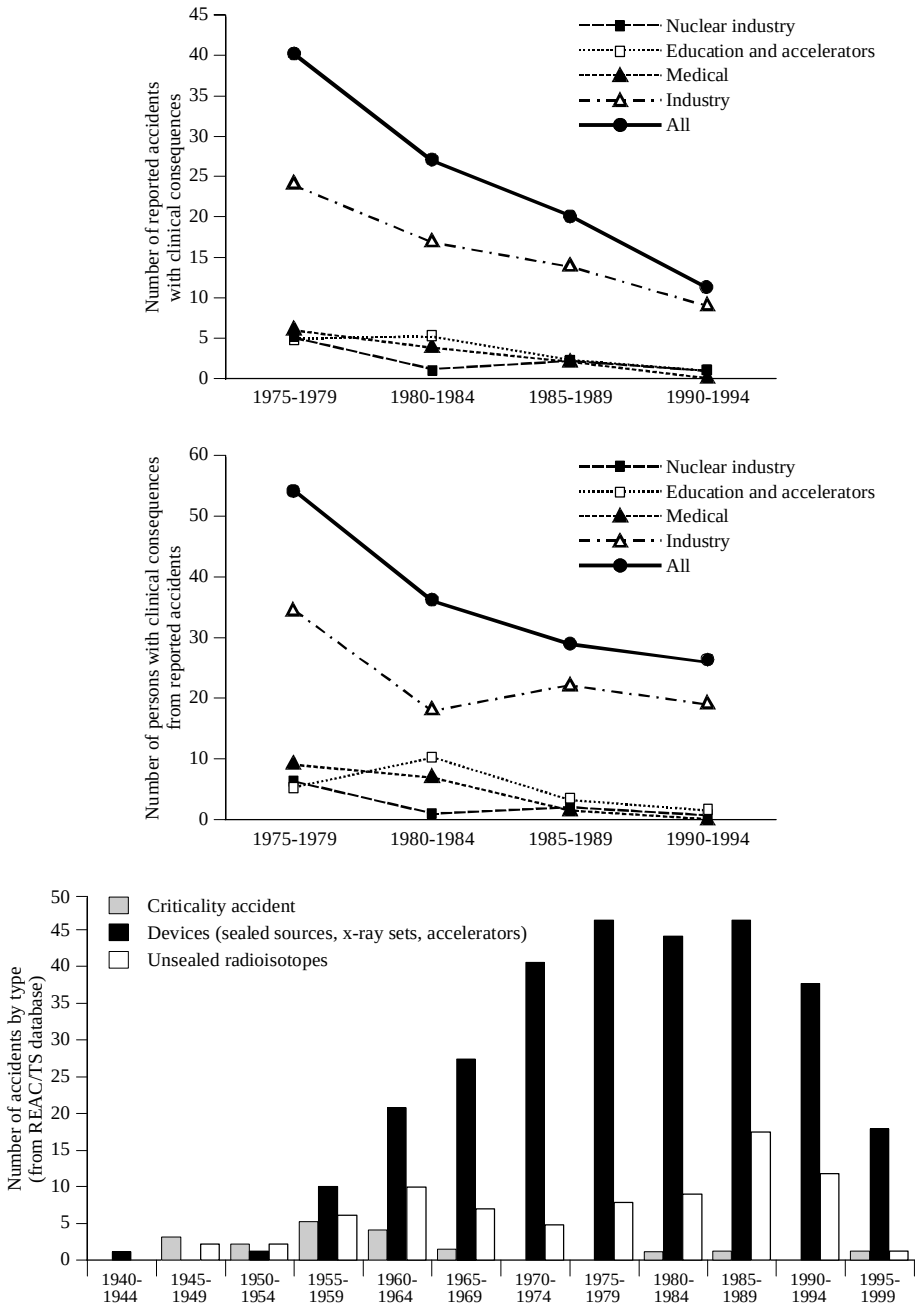

Figure XIV. Trends in accidents with clinical consequences.

295. ***Irradiators.*** Use of industrial gamma and electron beam irradiators for a range of industrial purposes began in the late 1950s in industrialized countries and later spread to other countries. There are now more than 160 gamma irradiation facilities and over 600 electron-beam facilities in operation worldwide [I8]. During the early years of the industry (until 1975), no fatal accidents occurred, but since 1989, a number of serious accidents have been reported [I4, I6, I23]. Between 1975 and 1994, six fatal accidents were reported. The first was in Italy in 1975, the second in Norway in 1982, and the third in El Salvador in 1989 [I23]. All of these were listed in the UNSCEAR 1993 Report [U3]. The three additional fatal accidents occurred during the period being covered here: the first and second in China and Israel in June 1990 and the third in Belarus in October 1991. There were also several serious non-fatal irradiator accidents during the period under review.

296. The fatal accident in China involved an irradiation facility (0.85 PBq ^{60}Co) used for sterilizing traditional Chinese medicines. One of the two doors in the entry route had been out of commission for some time due to a motor failure, and because of a power failure the interlock on the second door was not operable. Seven workers entered to re-arrange the product boxes but could not see the position of the source due to a metal shroud. Two of the workers received doses of 11 and 12 Gy and subsequently died. The fatal accident in Israel involved an irradiator facility (12.6 PBq ^{60}Co) used for sterilizing medical products and spices for the food industry. A distorted carton containing materials to be

irradiated became jammed on the conveyor transport system while the source was in the exposed position. The operator disregarded the warning signal from a gamma monitor, used an improper entry procedure to defeat the safety system, and entered the irradiation room. His whole-body dose was estimated to be about 10–15 Gy. Despite intensive medical care, he died of radiation effects 36 days after exposure [I4]. In the fatal accident in Belarus, an operator was exposed to radiation in an industrial irradiator, again following a jam in the product transport system, with the source (30 PBq ^{60}Co) in the exposed position. At the time of the accident, the irradiator was being used to sterilize medical equipment. The precise details of the actions of the operator are not known, although it is clear that the specified operating procedures were not followed and the safety features were circumvented. After reconstruction of the accident, a mean whole-body dose of approximately 11 Gy, with localized areas of up to 18 Gy, was estimated. Despite intensive medical treatment, the operator died 113 days after exposure [I6].

297. Three workers received significant doses from a linear accelerator of the van de Graaff type in France in July and August 1991. Reported doses ranged up to 40 Gy to the skin for the most irradiated of the three [C1, Z1]. According to the published reports, the accident was due to negligence and non-compliance with regulatory requirements. The accelerator was used to treat a granulated form of polytetrafluoroethylene. All three workers entered the facility through the exit of the conveyor. Their exposure was a result of the dark current associated with the accelerator after it had been switched off but with the accelerator voltage maintained to save time. The residual dose rate was a few grays per second. One suffered severe skin lesions; the other two were less seriously affected. An accelerator operator was overexposed at an industrial irradiation facility in Maryland in the United States in December 1991 [I8, S1]. The radiation source was a 3-MV accelerator for producing high electron beam currents for the processing of materials, typically polytetrafluoroethylene powder, wire, and plastic pellets. During maintenance, the operator placed his hands, head, and feet in the beam. This was done with the filament voltage of the electron source turned off but with the full accelerating potential on the high-voltage terminal. The operator was therefore exposed to the electron dark current, which was sufficient to produce dose rates of the order of 0.4–13 Gy s^{-1}. Three months after the accident, the four digits of the operator's right hand and most of the digits of his left hand had to be amputated; he also suffered hair thinning on the scalp after two weeks. A mean estimated dose to the man's fingers obtained by electron paramagnetic resonance spectrometry was of the order of 55 Gy. Also in November 1992, four workers were over-exposed in an irradiation facility in China [P1, S4]. The details obtained so far are sparse. The situation was described as involving a power loss and out-of-order safety interlocks. One of the workers suffered acute radiation syndrome.

298. ***Research accelerator.*** In November 1992, an individual entered an electron accelerator research facility in Hanoi, Viet Nam, without the operator's knowledge and unwittingly exposed his hands to the x-ray beam [I7]. He was adjusting a sample to be irradiated when, owing to the lack of safety systems and procedures to prevent it, the operator switched on the machine. Exposure was only a few seconds but at a very high dose rate, and the severity of radiation damage led within months to amputation of the whole of one hand and the fingers of the other. On the basis of a physical dosimetry calculation using all the information available, a most probable dose of 10–25 Gy was estimated for the left hand and 20–50 Gy for the right one.

299. ***Industrial radiography.*** An industrial radiographer in the United Kingdom died in 1992, probably as a result of substantial radiation exposure received over several years [L2]. His total average whole-body dose was estimated to be at least 10 Gy; a much larger dose to a hand required partial amputation of the hand. The cause of his death was acute myeloid leukaemia. The exact circumstances of his exposure were not established. He had, however, been working in industrial radiography since 1974. Until 1983, he worked with torch-type containers using ^{192}Ir sources. Thereafter he worked with wind-out, remotely operated ^{192}Ir sources. Doses recorded by his individual monitors were unremarkable, his lifetime recorded dose being 104 mSv.

300. Outside the period of direct interest there were other accidents involving industrial radiography. In France in 1995, an accident occurred during the handling of a 1 TBq ^{192}Ir gamma radiography source by an employee of a boiler-making firm [K2]. Although the employee's hands showed clinical effects, these were ignored until routine processing of the employee's dosimeter revealed a dose equivalent of 200 mSv. The circumstances of this accident have not yet been determined. The clinical development of the lesions and a thermographic analysis both indicated that the local dose had exceeded 30 Gy. In Iran in 1996, as a result of poor procedures in a confined situation, a worker received an estimated 3 Gy to the whole body and up to 50 Gy to the chest [O10] in connection with the use of an ^{192}Ir source. In 1999, in Peru, a welder picked up an ^{192}Ir source and put it in his pocket. He received approximately 3 Gy whole body but up to 100 Gy to a buttock [O10].

301. ***Criticality.*** In 1997, a worker at the nuclear weapons research centre of Arzamas-16 in the Nizhny Novgorod region of the Russian Federation received a whole-body gamma-neutron dose of 14 Gy with 200 Gy to the hands as a result of a criticality accident with a weapons-grade ^{235}U assembly. The worker died three days after the accident while undergoing treatment in a Moscow hospital [O10]. In 1999 at Tokai Mura, Japan a criticality accident occurred in a fuel conversion plant, involving the processing of highly enriched fuel for an experimental fast reactor. Using unauthorized procedures, the workers poured 16.6 kg of 18.8% enriched uranium into a precipitation tank, resulting in the critical excursion. The three workers involved received doses of approximately 17, 8, and 3 Gy; the two workers receiving the highest doses later died, the first 83 days and the second 211 days after the accident [I25, S8].

302. ***Loss of control of sources.*** In Xinzhou, China in 1992, a farmer who was working on a site demolishing a former irradiation facility picked up a cylindrical steel bar and put it in his pocket. He became ill the same day, and the bar went with him to the hospital. The bar contained a 0.4 TBq ^{60}Co source. The farmer, his brother and father all received doses in excess of 8 Gy and died; 14 other persons received doses in excess of 0.25 Gy. In Tammiku, Estonia, in 1994, a ^{137}Cs source (a few terabecquerels) thought to have been part of an irradiator was disposed of as scrap metal [I24]. It was recovered and stored in a source store with limited security. The store was broken into and the source removed. Six people, exposed to varying degrees up to 4 Gy whole body, developed a variety of lesions. One localized exposure was up to 1,800 Gy and the person died. Eleven frontier guards were exposed to one or more sources of ^{137}Cs with activities up to 150 GBq at the Lilo Training Centre near Tbilisi, Georgia [G3]. The sources had belonged to a former administration. The incident occurred over a period spanning 1996 and 1997. The sources were intended for training civil defence specialists or for calibration. Some of the sources had been removed from their containers, either still fixed in the source holder or separate from it. Information on the irradiation is incomplete, but it appears that at least one source was kept in the pocket of a coat. Each of the guards suffered from one or more acute localized irradiation lesions of varying seriousness; several suffered from nausea and vomiting. In Istanbul, Turkey, in 1998, a 3 TBq ^{60}Co therapy source inside a shielded transport container was sold as scrap. The individuals who purchased the source were unaware of the radiation hazard and proceeded to break open and dismantle the container in a residential area of Istanbul. Those involved started to suffer from the acute radiation syndrome, and further work was stopped. The cause of these symptoms was not recognized for some weeks. A total of 18 persons, including 7 children, were admitted to hospital. Five exhibited clinical effects of acute radiation exposure, with one person having signs of radiation-induced skin injuries on the fingers of one hand. The 3 TBq ^{60}Co source was recovered. It was initially thought that a second ^{60}Co source had also been dismantled in this accident, but that appears now not to have been the case [O10]. In Bangkok, Thailand in February 2000, poor source security resulted in three old radiotherapy heads being taken to a scrap yard. One source, estimated to be about 15.5 TBq ^{60}Co, was removed from its shielding. The resulting exposure caused 10 persons to be hospitalized, and three of these subsequently died.

303. While accidents causing death are relatively well known, there is likely to be a substantial under-reporting of other accidents, and even where information is available it is often fragmented. The UNSCEAR 1993 Report [U3] noted that a study [R6] of published material dealt with only about half the accidents covered in UNSCEAR reports. Recognizing that the lessons learned from accidents are important for preventing future accidents, a number of countries and international organizations have been setting up accident data-bases that should help future reporting. Examples are the IAEA's Radiation Event database (RADEV) [O10]; in the United Kingdom, the Ionizing Radiations Incident Database (IRID) [C6, T2]; and in the United States the Registry kept by REAC/TS [C7]. Caution needs to be exercised when comparing databases because of differences in scope, time frames, and categories. The REAC/TS database, which is summarized in Table 42 and Figure XIV, covers 1944 to 1999 and accidents involving the public and patients. Despite these differences and the inevitable bias towards data from the United States, which accounts for some two thirds of the data, the information paints an overall picture. Three quarters of the accidents occurred in the industrial sector, which is consistent with the UNSCEAR data. It also shows a downward trend in recent times, but unlike the UNSCEAR data, this does not start to be apparent until the beginning of the 1990s.

E. SUMMARY

304. Excluding the Chernobyl accident, the 98 occupational accidents reported to UNSCEAR for 1975–1994 covered 144 workers and included 8 fatalities. Owing to under-reporting, the actual number of accidents may have been two or three times greater, and there have been significant accidents connected with occupational uses of radiation but that exposed persons not directly employed in the original practice. Although the available data seem to suggest a downward trend, this should be treated with caution. Papers presented at a joint IAEA, European Community, Interpol, and the conference of the World Customs Organization (WCO) in 1998 on the safety of radiation sources and security of radioactive materials [C6, D5, L6] suggest that more accidents are coming to light.

CONCLUSIONS

305. Occupational radiation exposures have been evaluated for six broad categories of work: the nuclear fuel cycle, medical uses of radiation, industrial uses, defence activities, education and veterinary uses, and occupations where enhanced exposures to natural sources of radiation may occur. Results for 1990–1994 are summarized in Table 43 and, in abbreviated form, for the whole period of interest (1975–1994) in Table 44. The contribution of each category to overall levels of exposure and the trends with time are illustrated in Figure XV. The worldwide average individual and collective effective doses have been derived largely from data reported to the UNSCEAR Survey of Occupational Radiation Exposures, supplemented, where appropriate, by data from the literature.

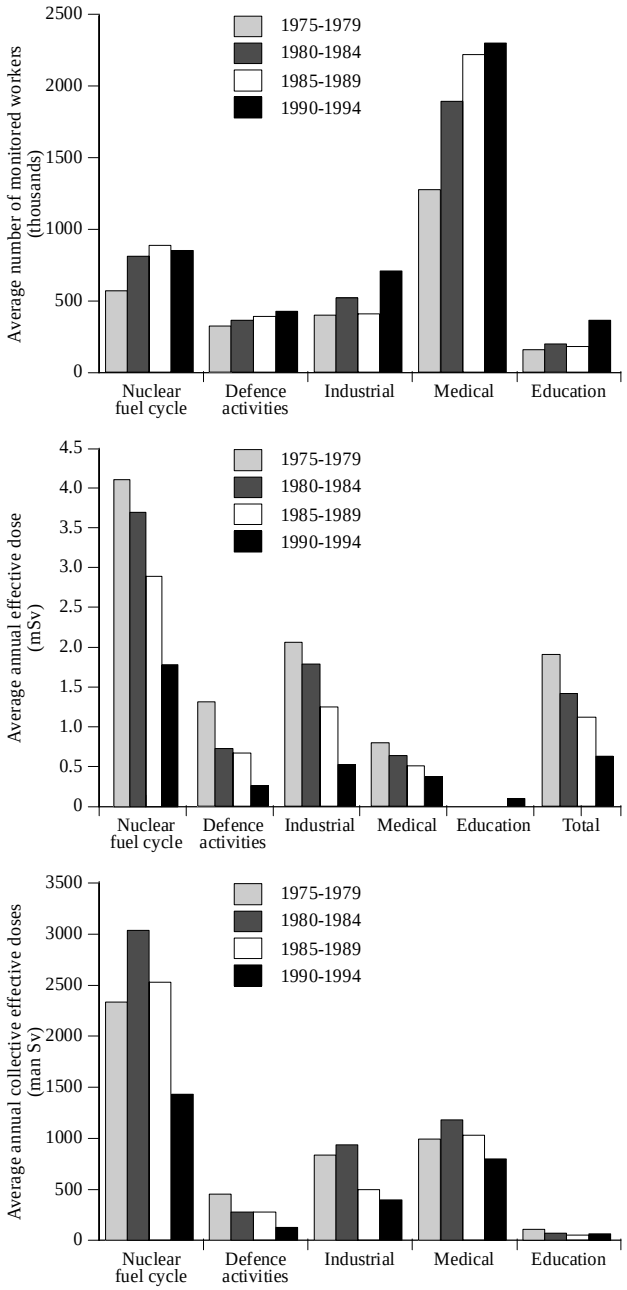

Figure XV. Trends in worldwide average annual number of monitored workers, doses to workers, and collective effective doses from man-made sources of radiation.

306. The worldwide average annual collective effective dose to workers from man-made sources of radiation in the period 1990–1994 is estimated to be about 2,700 man Sv. The collective effective dose from exposures to natural sources (in excess of average levels of natural background) is estimated to be about 11,700 man Sv. The largest component of this, 6,000 man Sv, comes from a category new to UNSCEAR reviews, namely, the exposure of workers to radon and its progeny significantly above background levels. Of the remainder, the largest components are 2,600 man Sv for coal mining and 2,000 man Sv for other mining operations (excluding uranium mining, which is dealt with in the nuclear fuel cycle). There are contributions of 800 man Sv to aircrew from exposure to cosmic radiation and 300 man Sv to those involved in the minerals processing industries. The estimated collective dose from natural sources of radiation is, however, associated with much greater uncertainty than that from man-made sources of radiation.

307. Of the annual collective effective dose from exposure to man-made sources of radiation (2,700 man Sv), about 50% arises from operations in the nuclear fuel cycle (1,400 man Sv), about 30% from medical uses (760 man Sv), about 14% from industrial uses of radiation (360 man Sv), about 4% from defence activities (100 man Sv), and about 2% from educational and veterinary activities (40 man Sv). The contribution from medical uses of radiation may, however, be an overestimate by a factor of 2 or more; most of the exposures from this source arise from low-energy x rays from diagnostic radiography, and the dosimeter readings, which are generally entered directly into dose records, may overestimate the effective dose by a large factor.

308. The average annual effective dose to monitored workers varies widely from occupation to occupation and also from country to country for the same occupation. The worldwide average annual effective doses to monitored workers in industry (excluding the nuclear fuel cycle), medicine, educational and veterinary activities are less than 1 mSv (about 0.51 mSv, 0.33 mSv, and 0.11 mSv, respectively). In particular countries, however, the average annual dose for some of these occupations is several millisievert or even, exceptionally, in excess of 10 mSv. The average annual effective doses to workers in the nuclear fuel cycle are, in most cases, larger than the doses to those in other occupations; for the fuel cycle overall, the average annual effective dose is about 1.75 mSv. For the mining of uranium, the average annual effective dose to monitored workers in countries reporting data was about 4.5 mSv, and for uranium milling operations, it was about 3.3 mSv. There are, however, very wide variations about these average values, with doses of about 50 mSv being reported in some countries. The average annual effective dose to monitored workers in LWRs is about 1.4 mSv, with doses about 20% greater, on average, in HWRs (1.7 mSv) and smaller by a factor of about 3, on average, in GCRs (0.5 mSv). Directly comparable data were not available for LWGRs, but other data suggest doses could be 10–15 mSv. The individual doses in fuel reprocessing are about 1.5 mSv, whereas those in fuel enrichment are much smaller, <0.1 mSv.

309. The percentage of monitored workers worldwide who worked with man-made sources of radiation and who received annual effective doses in excess of 15 mSv is estimated, on average, to have been less than 1% during the period 1990–1994. There is, however, considerable variation in this value by occupation. Typically, fewer than 0.1% of monitored workers in medicine and industry (excluding the nuclear fuel cycle and defence) are estimated to have received doses in excess of this level. For the nuclear fuel cycle as a whole, about 1% of monitored workers, on average, exceeded this level of annual effective dose. However, there is considerable variation between different stages of the fuel cycle (e.g. about 10% for uranium mining).

310. The percentage of the worldwide collective effective dose from all uses of man-made sources of radiation (or, more strictly, for those uses for which data have been reported) that arises from annual individual doses in excess of 15 mSv is estimated to have been about 13% during 1990–1994. There is, however, considerable variation in this value from one occupation to another. Typically, about 14% and 25%, respectively, of the collective dose in medicine and industry (excluding the nuclear fuel cycle and defence) is estimated to have arisen from annual individual doses in excess of this level. For the nuclear fuel cycle as a whole, about 11% of the collective dose arose from annual individual doses in excess of 15 mSv. There is, however, considerable variation between different stages of the fuel cycle: about 32% for uranium mining and milling, about 8% averaged over all but LWGR reactors, about 13% for fuel reprocessing, about 11% for fuel fabrication, and essentially zero for enrichment. In this Annex for the first time some data have been available on the percentages of workers exceeding other dose values, namely 10 mSv (NR_{10}), 5 mSv (NR_5), and 1 mSv (NR_1), and on the percentage of the collective dose coming from individual exposures exceeding these values, SR_{10}, SR_5, and SR_1. The data are not sufficiently robust to produce worldwide values, but for some of the practices they provide a better insight into the dose profiles underlying the limited indicators NR_{15} and SR_{15}. With the ongoing decreases in collective and individual doses, these additional parameters, i.e. NR_{10}, NR_5, NR_1 and SR_{10}, SR_5, SR_1, will become more important.

311. For the 1990–1994 period, significantly more data than in previous periods were available on average annual effective doses to measurably exposed workers. This has allowed for the first time reasonably robust worldwide estimates to be made for many of the practices. For the nuclear fuel cycle, the value was 3.1 mSv, higher by a factor of about 2 than the value for monitored workers (1.75 mSv). In each of the remaining categories for which an estimate was available the measurably exposed values were higher by a factor of about 4 than those for monitored workers: 1.4, 2.2, and 1.0 for medical uses, industrial uses, and educational/veterinarial uses, respectively. Considerable variation about these general factors is seen when individual practices are examined. For example, in uranium mining there is little difference between the average annual effective dose to workers of 4.5 mSv and the corresponding value of 5.0 mSv for measurably exposed workers, while in dentistry there is more than tenfold difference between the values of 0.06 mSv and 0.89 mSv for monitored workers and measurably exposed workers, respectively. When viewed together with the NR and SR parameters for each practice, these data provide a clearer picture of the dose profiles than was previously available.

312. The average annual effective dose to workers exposed to enhanced levels of radiation from natural sources, in particular in underground mines, varies considerably between mines and between countries. In coal mines, the average annual effective dose is estimated to be about 0.7 mSv. In other (non-uranium) mines, the worldwide average effective dose is estimated to about 2.7 mSv. Aircrew are estimated to receive an average annual effective dose of about 3 mSv.

313. ***Trends in exposures over the period 1975–1994.*** Trends in exposure from man-made sources are illustrated in Figure XVI for each of the main occupational categories considered in this Annex. No attempt has been made to discern any trends in occupational exposures from natural sources, because insufficient data are available to make meaningful estimates; the few data that do exist, however, suggest that exposures in mining operations and minerals processing in earlier periods were greater than those estimated here, possibly much greater. This is so because somewhat less attention was given in the past to the control and reduction of exposures in underground mining.

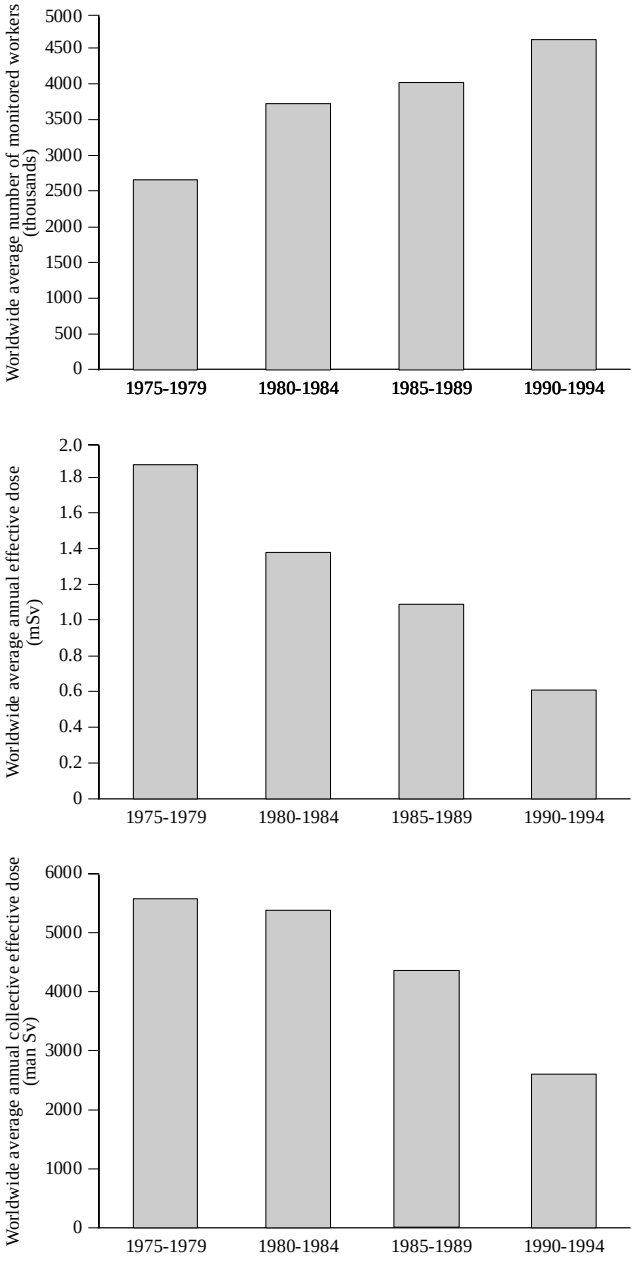

Figure XVI. Overall trends in worldwide occupational exposures to man-made sources of radiation.

314. The worldwide annual average number of workers involved with man-made uses of radiation is estimated to have increased from about 2.7 to about 4.6 million between the first and fourth five-year periods. The greatest increase (from about

1.3 to about 2.3 million) was in the number of monitored workers in medicine. The number of monitored workers in the nuclear fuel cycle also increased significantly, by about 50%, from about 0.6 million in the first period to about 0.9 million in the third period, but for 1990–1994 it dropped to 0.8 million. In defence activities and industrial uses there have been some variations, but overall both increased by about 30%, with defence activities rising from about 0.3 to 0.4 million and industrial uses rising from about 0.4 to 0.7 million workers.

315. The annual collective effective dose averaged over five-year periods for all operations in the nuclear fuel cycle varied little about the average value of 2,600 man Sv between 1975 and 1989 despite a three- to fourfold increase in electrical energy generated by nuclear means. The latter has continued to increase, but the average annual collective effective dose has fallen by a factor of about 2, to 1,400 man Sv. A significant part of this reduction came from the dramatic reduction in the uranium mining component, from 1,100 man Sv in 1985–1989 to 310 man Sv in 1990–1994. This estimated reduction is based on limited data, so its magnitude must be viewed with some caution. However, other indicators, such as the reduction in the amount of uranium mined, the closing of many underground mines, and a more general move to open-pit mining, support the view that a substantial reduction has taken place. In other parts of the nuclear fuel cycle the situation is more varied, for example, in reprocessing the downward trend in previous values, 53, 47, and 36 man Sv, has been reversed with an increase to 69 man Sv for 1990–1994, although to a large degree this simply reflects the inclusion of Russian data for the first time. However within the nuclear fuel cycle the other important element, other than mining, is reactor operation, which after increasing from 600 to 1,100 man Sv over the first three periods dropped to 900 man Sv for 1990–1994.

316. The normalized collective effective dose per unit energy generated has decreased with time for the fuel cycle overall and for most of its stages. For the fuel cycle overall, it has decreased by a factor of about 3, from about 20 man Sv $(GW\ a)^{-1}$ to about 9.8 man Sv $(GW\ a)^{-1}$, with most of the decrease occurring during the last two periods. For reactors between the first and second five-year periods, the normalized collective doses changed little, but large decreases occurred in the next two periods (first by a factor of 1.7 and then by a factor of 1.5). The UNSCEAR 1993 Report [U3] linked the first of these reductions to completion of most of the safety modifications following the accident at the Three-Mile Island reactor and to much greater attention paid by utilities and regulators to reducing occupational exposure in both existing and new reactors. This latter downward pressure on doses continued into the 1990–1994 period and indeed was given new impetus by changes in risk factors and consequent recommendations from ICRP [I12] for reductions in the dose limits. The above trends are also reflected in the average annual effective dose to monitored workers, which in the nuclear fuel cycle has been consistently reduced over the whole period, from 4.1 mSv to 1.75 mSv. There are some variations between parts of the nuclear fuel cycle and between countries. Of particular note is the fact that in the first three periods, the dose to monitored workers at LWGRs increased from 6.6 mSv to 13 mSv, and while no specific value for the fourth period was reported, other indicators suggest at least that the high level of exposure was maintained.

317. The worldwide average annual collective effective dose from all industrial uses of radiation (excluding the nuclear fuel cycle and defence activities) was fairly uniform over the period 1975–1984, at between 800 and 900 man Sv. It decreased, however, by a factor of almost 2 in the second half of the 1980s (to 490 man Sv) and then fell further, to about 360 man Sv, in 1990–1994. The same trend is reflected in estimates of individual dose: the average annual effective dose to monitored workers decreased from some 2.1 mSv in 1975–1979, through 1.8 mSv and 1.2 mSv, to 0.51 mSv in 1990–1994. It should be noted that in previous UNSCEAR reports industrial uses included a component from educational uses, which tended to distort the data. In this Annex, educational uses are dealt with in a separate category, and the industrial data for earlier years have been adjusted to remove the educational component. In defence activities, both the average individual and collective doses fell by a factor of about 4 over the whole period, from 1.3 mSv to 0.24 mSv and from 420 man Sv to 100 man Sv, respectively.

318. The worldwide average annual collective effective dose from all medical uses of radiation, about 1,000 man Sv, changed little over the first three five-year periods but then dropped significantly, to 760 man Sv, in 1990–1994. A clear downward trend is evident in the worldwide average effective dose to monitored workers, which decreased from about 0.78 mSv in the first five-year period to about 0.33 mSv in the fourth; there was, however, considerable variation between countries. The annual average number of monitored workers in medicine increased steadily over the four periods, almost doubling, from 1.3 million to 2.3 million. It is for this reason that the collective dose remained relatively uniform with time, notwithstanding the significant decrease in average individual dose. The extent to which some of these decreases in average individual dose are real or are merely artifacts due to changes in monitoring or recording practice warrants further analysis.

319. The percentage of monitored workers worldwide involved with all uses of man-made sources of radiation who received annual effective doses in excess of 15 mSv has decreased progressively, from an average of about 5% in the first period to 3% in the third period, and to less than 1% for 1990–1994. This same downward trend is evident in the percentages of nuclear fuel cycle and medical workers worldwide receiving annual doses in excess of that same level. The tabulated data for medical workers show an increase in the third period. The increase is more apparent than real, however, and is due to the inclusion for that period of data from a country that had previously not reported data, and which significantly increased the worldwide estimate. If that country were excluded, the trend would be downwards for medical workers throughout the period [U3]. For industrial workers worldwide (excluding the nuclear fuel cycle and defence), the trend is less consistent but overall has been downward.

320. The percentage of the worldwide annual collective effective dose from all man-made uses of radiation arising from annual individual doses in excess of 15 mSv also decreased progressively, from about 45% to about 36%, on average, between the first and third five-year periods. This decrease was greater between the third and fourth periods, with a value for 1990–1994 of 13%. The same downward trend is evident for the collective dose from the nuclear fuel cycle and from medical uses of radiation. The tabulated data for medical uses show an increase in the third period; however, for the reasons set out above, this increase is merely an artifact of the data, and the trend has in fact been downwards over the whole period. For industrial workers, there is little evidence of any clear trend with time in the fraction of the collective dose arising from annual doses in excess of 15 mSv, although over the whole period it has fell from 35% to 25%.

321. Occupational exposures to workers caused by accidents give an added component of dose or injury to those involved. The data compiled indicate that most of the accidents occurred in the industrial use of radiation and that most of them involved industrial radiography sources. The great majority of accidental exposures of sufficient magnitude to cause clinical effects were associated with localized exposures to the skin or hands. From 1975 to 1994, 36 people died as a result of radiation exposures received in accidents; 28 of these deaths were at Chernobyl. A significant feature of the more recent accidents is the three fatal accidents in industrial irradiation facilities: in El Salvador, 1989 [I23]; in Israel, 1990 [I4]; and in Belarus, 1991 [I6]. From 1975 to 1994, about 98 accidents to workers worldwide with actual clinical consequences were reported. Because non-fatal accidents may be under-reported, the actual number may have been somewhat greater.

322. The estimates of occupational radiation exposure in this Annex have benefited from a much more extensive and complete database than was previously available to the Committee. The efforts by countries to record and improve dosimetric data were reflected in the responses to the UNSCEAR Survey of Occupational Radiation Exposures and have led to improved estimates of occupational exposures.

323. The Committee's current estimate of the worldwide collective effective dose from man-made sources for the early 1990s, 2,700 man Sv, is lower by a factor of about 2 than that made by the Committee for the late 1970s. A significant part of the reduction comes in the nuclear power fuel cycle, particularly in uranium mining. However, reductions are seen in all the main categories: industrial uses, medical uses, defence activities, and education. This trend is also reflected in the worldwide average annual effective dose, which has fallen from about 1.9 mSv to 0.6 mSv.

324. No attempt has been made to deduce any trend in the estimates of dose from occupational exposure to natural sources of radiation, as the supporting data are somewhat limited. The UNSCEAR 1988 Report [U4] made a crude estimate of about 20,000 man Sv from this source, which was subsequently revised downward to 8,600 man Sv in the UNSCEAR 1993 Report [U3]. The comparable figure for 1990–1994 is 5,700 man Sv; however an important new element has been added for this period, namely occupational exposure to elevated levels of radon and its progeny, bringing the overall estimate to 11,700 man Sv. This is still considered to be a crude estimate and much better data are required. This will be a challenge for the next assessment by the Committee of occupational radiation exposures.

Table 1
Occupational categories used by UNSCEAR for evaluating exposure

Exposure source	*Occupational categories*
Nuclear fuel cycle	Uranium mining Uranium milling Uranium enrichment and conversion Fuel fabrication Reactor operation Fuel reprocessing Research in the nuclear fuel cycle
Medical uses	Diagnostic radiology Dental radiology Nuclear medicine Radiotherapy All other medical uses
Industrial uses	Industrial irradiation Industrial radiography Luminizing Radioisotope production Well-logging Accelerator operation All other industrial uses
Natural sources	Civilian aviation Coal mining Other mineral mining Oil and natural gas industries Handling of minerals and ores
Defence activities	Nuclear ships and support activities All other defence activities
Miscellaneous	Educational establishments Veterinary medicine Other specified occupational groups

Table 2
Dose monitoring and recording procedures for occupational exposure
Data from UNSCEAR Survey of Occupational Exposures

Country / area	*Occupation*	*Minimum detectable level (MDL) or recording level (mSv)*	*Dose recorded when less than MDL (mSv)*	*Dose recorded for lost dosimeters*
Argentina	All	0.1	0.00	
Australia [a]	All	0.01 x ray 0.07 gamma ray	0.00	
Brazil [a b]	All	0.2	0.00	Average value
Bulgaria	Reactor operation Nuclear medicine and radiotherapy All other medical uses Industrial radiography – x-ray All other	1.00 2.00 0.40 0.40 2.00	0.33 1.00 0.20 0.20 1.00	
Canada	All	0.20	0.00	
China		0.03	0.015	
China, Taiwan Province [b]	Reactor operation (PWR) Reactor operation (BWR) All other	0.05 0.08 0.08	0.00 0.00 0.00	Average of colleagues' doses for same period
Croatia	All	0.05	0.00	
Cuba	All	0.20	0.20	
Cyprus	All	0.20	0.05 (1990) 0.00 (1991–1994)	
Czech Republic [b]	Reactor operation Research in the nuclear fuel cycle All other	0.10 1.20 0.05	0.00 0.00	
Denmark [b c]	Research in the nuclear fuel cycle All other	0.20 0.10	0.00 0.00	0.00 0.00
Ecuador	All	0.20 or 0.10 (different laboratories)		
Finland [b]	Reactor operation Other	0.10 0.30	0.00 0.00	
France	Nuclear fuel cycle	1990-1993 0.15 COGEMA 0.10 EDF 0.35 CEA 1994 0.20 All	0.00	
Gabon	Uranium mining and milling All other	0.99 0.01	calculated 0.01	
Germany	Mining (other than uranium) All other	0.001 0.10	0.00 0.00	Attributed by controlling authority
Greece [c]	All	0.20	0.00	
Hungary	Reactor operation All other	0.10 0.35	0.00 0.00	
Iceland	Well logging Medical uses	0.20 0.05	0.00 0.00	
India	All	0.05	0.00	
Indonesia	Reactor operation Radioiosotope production Well loggers Educational establishments	0.05	0.05	
	All other industry	0.01	0.01	

Table 2 (continued)

Country / area	*Occupation*	*Minimum detectable level (MDL) or recording level (mSv)*	*Dose recorded when less than MDL (mSv)*	*Dose recorded for lost dosimeters*
Ireland	All	0.15 Film 0.10 TLD		
Japan	All	0.10	0.00	
Jordan	Radiotherapy	0.4	0	
Kuwait		0.2	0.1	
Mexico	All	0.25	0.00	5.00
Myanmar	All	0.01		
Netherlands	All	0.01		
Pakistan	All	0.10		
Peru	All	0.10	0.00	
Poland	All industrial uses	0.50	0.25	
Slovakia	All	0.10	0.00	
Slovenia	Nuclear fuel cycle Diagnostic and dental radiology Nuclear medicine Radiotherapy Industrial radiography All other industrial uses	0.01 0.04 0.1 0.005 0.1 0.1	 0.00 0.10 0.00 0.10 0.00	
South Africa	All	0.20	0.00	
Sri Lanka	All	0.05		
Sweden	All	0.1	0.00	
Switzerland	All	0.01	0.00	
Syria	All	0.20	0.10	
Syrian Arab Rep.	All those using devices	0.2	0.00	Mean value for last 12 months
Tanzania	All	0.10		
Thailand	Reactor operation Radioisotope production Nuclear medicine and radiotherapy All other	0.2 0.2 0.15 0.02	0.00 0.00 0.00 0.00	
United Kingdom	All	0.1	0.00	

a All data refer to external exposure.
b Doses to contractors included.
c Corrections made to avoid double entries.

Table 3
Exposures to workers from uranium mining [a] [b]
Data from UNSCEAR Survey of Occupational Exposures

Country / area and period	*Annual [c] amount of ore extracted (kt U)*	*Equivalent amount of energy (GW a)*	*Monitored workers [d] (thousands)*	*Measurably exposed workers (thousands)*	*Annual collective effective dose*			*Average annual effective dose (mSv)*		*Distribution ratio (number of workers)*				*Distribution ratio (collective dose)*			
					Total [d] (man Sv)	*Average per unit uranium extracted (man Sv per kt)*	*Average per unit energy generated (man Sv per GW a)*	*Monitored workers*	*Measurably exposed workers*	NR_{15}	NR_{10}	NR_5	NR_1	SR_{15}	SR_{10}	SR_5	SR_1
Argentina [e]														0.95			
1975–1979	0.108	0.492	0.37		4.89	45.3	9.9	13.2		0.54							
1980–1984	0.146	0.664	0.95		2.29	15.7	3.4	2.41									
1985–1989	0.465	2.77	0.51		1.25	2.7	0.59	2.45		0.00				0.00			
1990–1994	0.071	0.423	0.21	0.13	0.36	5.07	0.85	1.70	2.73	0.00	0.00	0.00	0.62	0.00	0.00	0.00	1.00
Australia																	
1985–1989	(3.60)		0.46	0.46	1.88	(0.52)		4.11	4.11	0.05				0.19			
1991–1994	(2.82)		0.28	0.26	0.37	0.13		1.33	1.43	0.00	0.00	0.01	0.51	0.00	0.01	0.04	0.86
Canada [f g h]																	
1975–1979	6.82	31.0	6.22	5.47	41.2	6.04	1.33	6.62	7.53	0.20				0.57			
1980–1984	8.22	37.5	8.88	7.42	50.6	6.16	1.35	5.70	6.82	0.23				0.62			
1985–1989	11.81	53.5	6.28	5.24	31.6	2.68	0.59	4.80	6.04	0.21				0.67			
1990-1994 [e]	9.00	40.90	2.43	1.94	8.69	0.97	0.21	3.58	4.46	0.04	0.11	0.26	0.58	0.18	0.44	0.75	0.96
China																	
1985–1989	(0.80)		6.6		114			17.3									
1990–1994	(0.76)		[2.1]		[48]												
Czech Rep. [i j]							7.45										
1975–1979	1.78	8.11	9.06		60.4	33.9	5.47	6.67									
1980–1984	2.02	9.19	8.48		50.2	24.8		5.92									
1985–1989	1.96	8.93	7.46		36.9	18.8	4.14	4.95		0.12				0.28			
1990–1994	0.60	2.72	1.36	1.03	20.6	34.5	7.59	15.2	15.3	0.46	0.68	0.88	0.99	0.68	0.87	0.97	1.00
France																	
1983–1984	1.85	8.42	1.28	1.25	17.0	9.18	2.02	13.3	13.6	0.48							
1985–1989	2.99	13.58	1.75	1.69	13.2	4.42	0.97	7.56	7.83	0.31							
1990–1994	(2.05)		1.00	1.00	8.47	4.13		8.48	8.48	0.18	0.31	0.60	0.86				

Table 3 (continued)

Country / area and period	*Annual [c] amount of ore extracted (kt U)*	*Equivalent amount of energy (GW a)*	*Monitored workers [d] (thousands)*	*Measurably exposed workers (thousands)*	*Annual collective effective dose*			*Average annual effective dose (mSv)*		*Distribution ratio (number of workers)*				*Distribution ratio (collective dose)*			
					Total [d] (man Sv)	*Average per unit uranium extracted (man Sv per kt)*	*Average per unit energy generated (man Sv per GW a)*	*Monitored workers*	*Measurably exposed workers*	NR_{15}	NR_{10}	NR_5	NR_1	SR_{15}	SR_{10}	SR_5	SR_1
Gabon																	
1985–1989	(0.90)		0.24		5.06			21.0									
1990–1994	0.60	2.72	0.19		2.58	4.30	0.95	13.4		0.36	0.55	0.72	0.88				
Germany [k]																	
1975–1979	6.26	28.5	14.7	14.7	160	25.5	5.61	10.9	10.9	0.46				0.72			
1980–1984	4.73	21.5	15.1	15.1	147	31.0	6.82	9.69	9.69	0.42				0.65			
1985–1989	4.07	18.5	16.1	1.61	133	32.7	7.18	8.24	8.24	0.31				0.57			
1990–1994	0.77	3.48	4.71	4.68	20.2	26.4	5.82	4.30	4.33	0.05	0.16	0.42	0.82	0.13	0.35	0.71	0.96
India [l]																	
1981–1984	0.13	0.58	1.16		13.8	108	23.7	11.9									
1985–1989	0.15	0.68	1.35		15.2	101	22.3	11.3									
1990–1994	(0.18)		[0.43]		[8.1]												
Slovenia [m]																	
1990–1994	0.01	0.05	0.11	0.11	0.27	23.3	5.13	2.46	2.62	0.00	0.00	0.27	0.53	0.00	0.00	0.61	0.87
Spain																	
1985–1989	0.36	1.64	0.38	0.23	0.26	0.71	0.15	0.68	1.14								
1990–1994	0.24	1.09	0.27	0.13	0.10	0.40	0.09	0.26	0.34	0.00	0.00	0.00	0.02	0.00	0.00	0.00	0.19
South Africa [n]																	
1975–1979	3.27	14.9	79.0		346	107	23.3	4.39									
1980–1984	5.07	23.0	93.6		399	78.8	17.3	4.27									
1985–1989	3.53	16.0	82.2		278	78.8	17.3	3.38									
1990–1994	(1.83)		[26]		[64]												
Russian Fed.																	
1985–1989								16.3									
1990–1994	(2.84)		2.89	2.89	6.39			2.21	2.21	0.01				0.09			
United States																	
1975–1979	5.51	25.1	6.85		30.9	5.60	1.23	4.51									
1980–1984	5.01	22.8	5.89	3.83	19.4	3.86	0.85	3.29	5.05								
1985–1989	2.27	10.3	0.77	0.62	2.68	1.18	0.26	3.46	4.33								
1990–1994	(2.22)		[0.25]		[1.2]												

Table 3 (continued)

Country / area and period	*Annual [c] amount of ore extracted (kt U)*	*Equivalent amount of energy (GW a)*	*Monitored workers [d] (thousands)*	*Measurably exposed workers (thousands)*	*Annual collective effective dose*			*Average annual effective dose (mSv)*		*Distribution ratio (number of workers)*				*Distribution ratio (collective dose)*			
					Total [d] (man Sv)	*Average per unit uranium extracted (man Sv per kt)*	*Average per unit energy generated (man Sv per GW a)*	*Monitored workers*	*Measurably exposed workers*	NR_{15}	NR_{10}	NR_5	NR_1	SR_{15}	SR_{10}	SR_5	SR_1
Total [o p]																	
1975–1979	22.7	103.3	116		643	28.3	6.25	5.54		0.39				0.69			
1980–1984	26.1	118.0	135		686	26.2	5.81	5.81		0.33				0.61			
1985–1989	30.3	136.2	116		509	16.8	3.74	4.40		0.26				0.53			
1990–1994	19.0	85.4	13.5	12.6	68.1	3.58	0.80	5.07	5.39	0.10	0.21	0.42	0.76	0.32	0.54	0.80	0.97
	[24.0]		[42.3]		[189]												
World [q]																	
1975–1979	52	240	240		1300	26	5.7	5.5		0.37				0.69			
1980–1984	64	290	310		1600	23	5.5	5.1		0.30				0.61			
1985–1989	59	270	260		1100	20	4.3	4.4		0.25				0.52			
1990–1995	39	180	69	62	310	7.9	1.72	4.5	5.0	0.10	0.21	0.42	0.76	0.32	0.54	0.80	0.97

a The data are annual averages over the periods indicated.

b Previously data for underground and open pit mines was presented separately. For this table the data for previous periods has been combined, as the 1990–1994 UNSCEAR survey made no distinction.

c Where countries did not report the amount of ore extracted, the value quoted in [O3] is given in round brackets. Where other significant data was missing, the Committee made estimates given in square brackets. These estimates based on the average trends for countries reporting for both 1985–1989 and 1990–1994.

d In the absence of reported data for 1990–1995 the Committee has estimated numbers of monitored workers and collective dose on the basis of the overall trend for those countries reporting for both 1985–1989 and 1990-1995. See also footnote *c*.

e Data contain a contribution from uranium milling.

f Part of Canada's production goes to the United States of America where it is used in reactors that have a different burn rate than the CANDU reactors used in Canada.

g For 1975–1983 the reported data contain a contribution from milling.

h Reported data from before 1981 did not include external radiation; an external dose of 2.6 mSv (the average external dose to monitored workers in 1982–1983) has been added here to reported doses before 1981. The reported distribution ratios before 1981 did not take account of external exposure and are therefore underestimates.

i Data for 1985–1989 are for Czechoslovakia.

j Exposures from inhalation of dust are not included; measurements have indicated that it would contribute less than 3 mSv to the annual committed effective dose.

k The 1975–1989 data is from the German Democratic Republic. During the period reported many of the mining operations in Germany were closed down; reducing the amount of ore extracted from 2.97 kt in 1990 to 0.05 kt in 1994.

l The contribution from the dust is very small because of the low grade of the ore and has been ignored.

m Uranium mining occurred for only six months in 1990; since then, further exposures have been from maintenance work only.

n Data are for gold mines. In 5 mines out of 40, uranium is produced as a by-product. The numbers of workers and total and normalized collective doses are those that can be attributed to uranium mining. Estimates of dose have been made for the whole workforce from measurements and knowledge of working environments. This average dose has been assumed for the period, and the tabulated collective doses are the product of this dose and the reported annual number of workers.

o These data should be interpreted with care, particularly when comparisons are made between different periods, as the countries included in the respective summations may differ from one period to another. The distribution ratios are averages of those reported, and the data on these are often less complete than data for the other quantities.

p The first line of the 1990–1994 value is for those countries that reported data for this period and excludes countries for which the Committee deemed it necessary to make estimates. The second line of the 1990–1994 values includes the estimates made Committee for China, India, South Africa and the United States.

q For 1990–1994 the worldwide estimates are extrapolated from the total amount of uranium mined worldwide relative to the sum of the total for which the Committee made an estimate.

Table 4
Exposures to workers from uranium milling [a] [b]
Data from UNSCEAR Survey of Occupational Exposures

Country / area and period	*Annual amount of ore refined (kt U)*	*Equivalent amount of energy [c] (GW a)*	*Monitored workers (thousands)*	*Measurably exposed workers (thousands)*	*Annual collective [d] effective dose*			*Average annual effective dose (mSv)*		*Distribution ratio (number of workers)*				*Distribution ratio (collective dose)*			
					Total (man Sv)	*Average per unit uranium refined (man Sv per kt)*	*Average per unit energy generated (man Sv per GW a)*	*Monitored workers*	*Measurably exposed workers*	NR_{15}	NR_{10}	NR_5	NR_1	SR_{15}	SR_{10}	SR_5	SR_1
Australia																	
1988–1989	4.20	19.1	0.61	0.61	2.04	0.49	0.11	3.36	3.36	0.00				0.00			
1991–1994			0.45	0.35	0.19			0.43	0.55	0.00	0.00	0.00	0.14	0.02	0.02	0.04	0.59
Canada [e]																	
1975–1979	4.31	19.6	0.668	0.458	0.66	0.153	0.034	0.99	1.44								
1980–1984	5.50	25.0	0.852	0.356	0.37	0.067	0.015	0.43	1.04								
1985–1989	9.29	42.2	0.83	0.66	1.30	0.14	0.031	1.56	1.95	0.01				0.01			
1990–1994			0.35	0.32	0.64			1.84	2.03	0.00	0.00	0.04	0.67	0.00	0.01	0.12	0.77
China																	
1985–1989			3.05		9.67			3.17									
Czechoslovakia [f]																	
1980–1984	1.82	8.27	1.13		11.4	6.28	1.38	10.1									
1985–1989	1.81	8.24	1.19		11.6	6.42	1.41	9.74									
France [g]																	
1988–1989	2.77	12.6	0.34	0.33	2.04	0.74	0.16	5.43	6.28								
German Dem.Rep. [h]																	
1975–1979	5.47	24.9	3.45	3.45	43.8	8.00	1.76	12.7	12.7								
1980–1984	4.60	20.9	3.24	3.24	34.1	7.40	1.63	10.5	10.5								
1985–1989	4.07	18.5	2.99	2.99	24.8	6.10	1.34	8.30	8.30								
India [i]																	
1981–1984	0.128	0.58	0.49		3.58	27.9	6.15	7.35									
1985–1989	0.150	0.68	0.58		3.40	22.6	4.97	5.86									
South Africa																	
1979	3.60	16.4	0.388	0.085	0.07	0.018	0.004	0.17	0.78								
1980–1984	4.46	20.3	0.648	0.277	1.93	0.432	0.095	2.97	6.95								
1985–1989	3.00	13.7	0.643	0.257	1.08	0.360	0.079	1.68	4.20								

Table 4 (continued)

Country / area and period	*Annual amount of ore refined (kt U)*	*Equivalent amount of energy* [c] *(GW a)*	*Monitored workers (thousands)*	*Measurably exposed workers (thousands)*	*Annual collective* [d] *effective dose*			*Average annual effective dose (mSv)*		*Distribution ratio (number of workers)*				*Distribution ratio (collective dose)*			
					Total (man Sv)	*Average per unit uranium refined (man Sv per kt)*	*Average per unit energy generated (man Sv per GW a)*	*Monitored workers*	*Measurably exposed workers*	NR_{15}	NR_{10}	NR_5	NR_1	SR_{15}	SR_{10}	SR_5	SR_1
United States																	
1975–1979	8.90	40.5	0.30	0.1	0.03	0.004	0.001	0.11	0.34								
1980–1984	16.8	76.4	4.80	3.0	4.48	0.267	0.059	0.93	1.49								
1985–1989	4.30	19.6	1.00	0.6	0.95	0.221	0.049	0.95	1.59								
Total																	
1975–1979	18.7	85	4.4		44.5	2.38	0.52	10.1									
1980–1984	28.8	131	10.4		53.2	1.85	0.41	5.1									
1985–1989	22.4	102	6.98		43.7	1.95	0.43	6.30		0.18				0.43			
1990–1994			0.80	0.66	0.83			1.04	1.25	0.00	0.00	0.02	0.37	0.01	0.01	0.08	0.68
World [j]																	
1975–1979	53	240	12		124	2.36	0.52	10.1									
1980–1984	64	290	23		117	1.84	0.41	5.1									
1985–1989	58	260	18		116	2.01	0.44	6.3									
1990–1994	39	180	6		20	0.5	0.11	3.3									

a The data are annual averages over the periods indicated.
b There is insufficient data to make a world estimate.
c Estimated on the simplifying assumption that all the milled uranium is used in LWRs. The assumed fuel cycle requirement is 220 t uranium $(GW\ a)^{-1}$.
d Doses from inhalation of radon daughters estimated using a conversion factor of 5.0 mSv WLM^{-1}.
e For 1975–1983, the quoted values are for extraction only; data for milling for this period are reported together with the mining data.
f Contribution from internal exposure is small and has not been explicitly estimated.
g The contribution from radon also includes the contribution from inhalation of ore dust.
h Doses estimated on basis of grab samples.
i The contribution of dust is small because of the low grade of the ore and has been ignored
j The worldwide estimate is based on the amount of ore refined being equal to the amount mined and on the downward trends for monitored workers and collective dose shown in Australia and Canada for the periods 1985–1989 to 1990–1994.

Table 5
Exposures to workers from uranium enrichment and conversion [a]
Data from UNSCEAR Survey of Occupational Exposures

Country / area and period	Annual amount of separative work (MSWU)	Electrical energy equivalent of uranium [b] (GW a)	Monitored workers (thousands)	Measurably exposed workers (thousands)	Annual collective effective dose			Average annual effective dose (mSv)		Distribution ratio (number of workers)				Distribution ratio (collective dose)			
					Total (man Sv)	Average per unit uranium enriched (man Sv per MSWU)	Average per unit energy generated (man Sv per GW a)	Monitored workers	Measurably exposed workers	NR_{c15}	NR_{10}	NR_5	NR_1	SR_{15}	SR_{10}	SR_5	SR_1
Canada [d]																	
1990–1994			0.33	0.22	0.29			0.88	1.32	0.00	0.00	0.02	0.30	0.00	0.01	0.16	0.81
France																	
1979			2.36	0.068		0.037		0.016	0.54								
1980–1984			2.33	0.050		0.035		0.015	0.69								
1985–1989			1.77	0.01	0.003			0.002	0.37	0.00							
1990–1994			4.04	0.17	0.08			0.02	0.44	0.00	0.00	0.00	0.04				
Japan																	
1987–1989	0.2		0.140		0												
1990–1994			3.60		0.06			0.00									
Netherlands																	
1985–1989			0.01		0.01												
1990–1994			0.08	0.06	0.02			0.28	0.36	0.00	0.00	0.00	0.06	0.00	0.00	0.00	0.33
South Africa																	
1985–1989	0.10		0.09		0.035	0.34	0.044	0.38									
1990–1994			0.31	0.26	0.25			0.81	0.91	0.00	0.00	0.01	0.28	0.00	0.02	0.07	0.67
United Kingdom																	
1975–1979			0.35		0.040			0.12									
1980–1984	0.06	0.47	0.22		0.049	0.665	0.086	0.22									
1985–1989	0.29	2.23	0.16		0.023	0.170	0.022	0.15									
1990–1994	0.63	5.11	0.77		0.15	0.037	0.005	0.20									
United States																	
1975–1979 [d]			10.3	8.34	5.14			0.50	0.62								
1980–1984			1.45	0.65	0.62			0.42	0.94								
1985–1989			2.92	0.93	0.36			0.12	0.38								
1990–1994 [e]			3.42	1.14	0.43			0.12	0.37								

Table 5 (continued)

Country / area and period	*Annual amount of separative work (MSWU)*	*Electrical energy equivalent of uranium* [b] *(GW a)*	*Monitored workers (thousands)*	*Measurably exposed workers (thousands)*	*Annual collective effective dose*			*Average annual effective dose (mSv)*		*Distribution ratio (number of workers)*				*Distribution ratio (collective dose)*			
					Total (man Sv)	*Average per unit uranium enriched (man Sv per MSWU)*	*Average per unit energy generated (man Sv per GW a)*	*Monitored workers*	*Measurably exposed workers*	NR_{15}^{c}	NR_{10}	NR_{5}	NR_{1}	SR_{15}	SR_{10}	SR_{5}	SR_{1}
Total [f]																	
1975–1979			11		5.3			0.46		0.00				0.00			
1980–1984			4.3		0.78			0.18		0.00	0.00	0.00	0.08	0.00	0.02	0.12	0.73
1985–1989			5.0		0.43			0.08		0.00							
1990–1994			12.6		1.28			0.10		0.00							

a The data are annual averages over the periods indicated.
b Estimated on the simplifying assumption that all the enriched uranium is used in LWRs. The assumed fuel cycle requirement is 0.13 MSWU per GWa.
c The values are for the monitored workforce.
d Data relate to uranium refining.
e Data is taken from Department of Energy reports [D4].
f Total of reported data. These data should be interpreted with care particularly when making comparisons between different periods, as the countries included in the respective summation may differ from one period to another.

Table 6
Exposures to workers from fuel fabrication [a] [b]
Data from UNSCEAR Survey of Occupational Exposures

Country / area and period	Average annual production of fuel (kt U) [c]	Equivalent amount of energy [c] [d] (GW a)	Monitored workers (thousands)	Measurably exposed workers (thousands)	Annual collective effective dose			Average annual effective dose (mSv)		Distribution ratio (number of workers)				Distribution ratio (collective dose)			
					Total (man Sv)	Average per unit mass of fuel (man Sv per kt)	Average per unit energy generated (man Sv per GW a)	Monitored workers	Measurably exposed workers	NR_{15} [e]	NR_{10}	NR_5	NR_1	SR_{15}	SR_{10}	SR_5	SR_1
Argentina [f]																	
1980–1984	0.030	0.14	0.10		0.025	0.84	0.18	0.24									
1985–1989	0.046	0.21	0.11		0.024	0.51	0.11	0.22									
1990–1994	0.12	0.56	0.07	0.06	0.08	0.64	0.14	1.07	1.37	0.00	0.00	0.01	0.28	0.00	0.00	0.05	0.82
Canada																	
1975–1979	0.61	3.38	0.53	0.34	0.68	1.12	0.20	1.27	1.99	0.00				0.03			
1980–1984	1.13	6.30	0.65	0.36	0.95	0.84	0.15	1.48	2.64	0.00				0.00			
1985–1989	1.41	7.81	0.43	0.28	1.02	0.73	0.13	2.37	2.62	0.00				0.01			
1990–1994	1.57	(8.70)	0.33	0.22	0.66	0.42		2.01	3.01	0.00	0.01	0.15	0.47	0.00	0.06	0.51	0.96
China																	
1990–1994	0.02	0.31	1.17	1.13	1.33	87.6	4.33	1.13	1.18	0.00	0.00	0.04	0.30	0.00	0.00	0.23	0.79
France																	
1990–1994	(1.26)	(34.0)	0.58	0.30	1.50			2.59	5.03	0.04	0.08	0.17	0.52				
Japan																	
1979	0.83	14.5	1.44		0.69	0.83	0.05	0.48									
1980–1984	1.07	18.1	2.13		1.38	1.29	0.08	0.64									
1987–1989	1.29	20.7	2.61		0.67	0.52	0.03	0.26									
1990–1994	(1.01)	(16.2)	1.66	0.46	0.37			0.23	0.81	0.00	0.00	0.00	0.08	0.00	0.00	0.08	0.74
Russian Fed.																	
1992–1994	(1.95)			0.43	1.53		3.60	0.00									
South Africa																	
1990–1994	(0.10)		0.30	0.25	0.24			0.81	0.97	0.00	0.00	0.00	0.28	0.03	0.04	0.06	0.56
Spain [g]																	
1986–1989	0.16	4.43	0.35	0.25	0.38	2.53	0.09	1.09	1.53								
1990–1994	0.14	(3.88)	0.34	0.12	0.07	0.54		0.22	0.42	0.00	0.00	0.00	0.03	0.00	0.00	0.00	0.25
Sweden [h]																	
1986–1989	0.26	7.01	0.35	0.09	0.21	0.82	0.03	0.61	2.29								
1990–1994	0.30	(8.09)	0.37	0.08	0.05	0.18		0.15	0.68	0.00	0.00	0.00	0.04	0.00	0.04	0.04	0.58

Table 6 (continued)

Country / area and period	*Average annual production of fuel (kt U)* [c]	*Equivalent amount of energy* [c d] *(GW a)*	*Monitored workers (thousands)*	*Measurably exposed workers (thousands)*	*Annual collective effective dose*			*Average annual effective dose (mSv)*		*Distribution ratio (number of workers)*				*Distribution ratio (collective dose)*			
					Total (man Sv)	*Average per unit mass of fuel (man Sv per kt)*	*Average per unit energy generated (man Sv per GW a)*	*Monitored workers*	*Measurably exposed workers*	NR_{15} [e]	NR_{10}	NR_5	NR_1	SR_{15}	SR_{10}	SR_5	SR_1
U. Kingdom																	
1975–1979	1.39	14.5	2.56		5.79	4.17	0.40	2.26		0.00							
1980–1984	1.20	12.9	2.91		5.16	4.30	0.40	1.77		0.00							
1985–1989	1.27	14.7	2.96		8.99	7.08	0.61	3.04		0.02							
1990–1994	(1.20)	(13.9)	3.08		5.64			1.83									
United States																	
1975–1979	0.95	25.8	11.1	5.85	19.0	19.8	0.73	1.71	3.24	0.01				0.39			
1980–1984	1.19	32.3	9.45	5.49	8.68	7.26	0.27	0.92	1.58	0.00				0.12			
1985–1989	1.92	51.8	9.95	3.88	4.51	2.35	0.09	0.45	1.16	0.00				0.02			
1990-1994 [i]	(2.12)	(57.2)	9.58	3.66	5.66			0.59	0.71	0.00	0.01	0.02	0.12	0.20	0.58	0.80	0.96
Total																	
1975–1979	3.13	46.6	14.8		26.7	8.53	0.57	1.8									
1980–1984	4.64	69.9	15.6		16.2	3.49	0.23	1.04									
1985–1989	6.35	104	17.9		17.0	2.67	0.16	0.94									
1990-1994 [j]	8.79	143	16.2	8.3	16.8	1.91	0.12	1.03	2.02	0.00	0.01	0.03	0.16	0.11	0.31	0.55	0.89
World																	
1975–1979	3.6	60	20		36	10.0	0.59	1.8		0.01				0.38			
1980–1984	6.1	100	21		21	3.44	0.21	1.0		0.00				0.11			
1985–1989	9.67	180	28		22	2.28	0.12	0.78		0.00				0.02			
1990–1994	11.3	210	21	10.6	22	1.91	0.10	1.03	2.02	0.00	0.01	0.03	0.16	0.11	0.31	0.55	0.89

a The data are annual averages over the periods indicated.
b The data in previous reports covered the different types of fuel separately. For this report the previous data for 1975–1989 has been aggregated for all fuel types.
c Where no values were reported for average annual production of fuel it has been assumed that the value equals the fuel requirements of that country. The data for this has been taken from OECD [O8, O9] and IAEA [I20, I21]. These estimates are shown in parentheses.
d The amounts of fuel required to generate 1 GW a of electrical energy by each reactor type are taken to be as follows: PWR: 37 t; HWR: 180 t; Magnox: 330 T; AGR 38 t.
e The values are for the monitored workforce.
f Contribution from internal exposure not included but estimated to be less than 10%.
g Calculation of distribution ratios based on data for 1993 and 1994.
h Data on average annual production relates to kt of UO_2.
i Calculation for SR distribution ratios based on data from 1993 and 1994.
j The total number reported for measurably exposed workers has been increased pro rata to the data for monitored workers to allow for those countries reporting a collective dose but not the number of measurably exposed workers.

Table 7
Exposures to workers from reactor operation [a]
Data from UNSCEAR Survey of Occupational Exposures

Country / area and period	Average number of reactors over the period	Average annual energy generated (GW a)	Monitored workers (thousands)	Measurably exposed workers (thousands)	Annual collective effective dose			Average annual effective dose (mSv)		Distribution ratio (number of workers)				Distribution ratio (collective dose)			
					Total (man Sv)	Average per reactor (man Sv)	Average per unit energy generated (man Sv per GW a)	Monitored workers	Measurably exposed workers	NR_{15}	NR_{10}	NR_5	NR_1	SR_{15}	SR_{10}	SR_5	SR_1
PWRs																	
Belgium																	
1975–1979	4.0	1.14	2.39		5.28	1.32	4.63	2.21									
1980–1984	5.2	2.01	4.50		10.1	1.94	5.00	2.24									
1985–1989	7.6	4.26	8.38		17.9	2.36	4.22	2.14									
1990–1994	7.0	4.82			9.61	1.37	1.99										
Brazil																	
1990–1994	1.0		1.03	0.39	0.93	0.93		0.90	2.39	0.00	0.01	0.06	0.21	0.04	0.19	0.52	0.92
Bulgaria																	
1990–1994	5.8	1.57	2.29		12.2	2.10	7.77	5.33									
China																	
1992–1994	1.67	0.56	0.82	0.46	0.43	0.26	0.75	0.52	0.92	0.00	0.01	0.02	0.10	0.09	0.15	0.33	0.65
China, Taiwan																	
1984	1.0	0.34	3.68		0.26	0.26	0.77	0.07									
1985–1989	2.0	1.06	2.52		1.41	0.71	1.34	0.56									
1990–1994	2.0	1.48	1.94	1.42	2.12	1.06	1.43	1.09	1.49	0.01	0.03	0.06	0.19	0.29	0.43	0.62	0.90
Czech Rep. [b]																	
1975–1977	1.0	0.11	0.87	0.08	0.09	0.09	0.79	0.10	1.17	0.00				0.12			
1980–1989	2.2	0.62	1.56	0.80	1.84	0.83	2.97	1.18	2.30	0.01				0.17			
1985–1989	7.0	2.11	4.14	2.43	3.97	0.57	1.88	0.96	1.64	0.01				0.12			
1990–1994	4.0	1.25	2.36	1.20	1.47	0.37	1.17	0.63	1.11	0.00	0.00	0.02	0.12	0.03	0.07	0.20	0.59
Finland																	
1977–1979	1.0	0.34	0.93	0.47	0.79	0.79	2.31	0.84	1.69								
1980–1984	1.8	0.67	1.26	0.73	1.80	1.00	2.71	1.43	2.48	0.01				0.07			
1985–1989	2.0	0.84	1.09	0.65	1.73	0.87	2.05	1.59	2.66	0.01				0.07			
1990–1994	2.0	0.77	1.24	0.77	2.45	1.23	3.20	1.97	3.19	0.01	0.05	0.14	0.38	0.12	0.32	0.64	0.95

Table 7 (continued)

Country / area and period	*Average number of reactors over the period*	*Average annual energy generated (GW a)*	*Monitored workers (thousands)*	*Measurably exposed workers (thousands)*	*Annual collective effective dose*			*Average annual effective dose (mSv)*		*Distribution ratio (number of workers)*				*Distribution ratio (collective dose)*			
					Total (man Sv)	*Average per reactor (man Sv)*	*Average per unit energy generated (man Sv per GW a)*	*Monitored workers*	*Measurably exposed workers*	NR_{15}	NR_{10}	NR_5	NR_1	SR_{15}	SR_{10}	SR_5	SR_1
France																	
1977–1979	3.5	1.93	3.40	0.89	4.34	1.24	2.24	1.28	4.87								
1980–1984	17.2	11.1	14.4	6.40	29.4	1.71	2.65	2.05	4.60	0.03							
1985–1989	41.0	28.3	29.7	16.8	78.9	1.92	2.79	2.65	4.68	0.05							
1990–1994	52.0	38.3			113	2.17	2.95										
Germany [c]																	
1975–1979	8.8	3.31	7.32		22.2	4.92	14.9	5.97		0.04				0.45			
1980–1984	11.6	6.34	11.7		43.0	6.94	13.3	6.79		0.06				0.44			
1985–1989	16.4	10.9	19.0	1.58	41.8	4.71	10.3	4.58	5.85	0.05				0.42			
1990–1994	14.0	12.5			27.1	1.94	2.17										
Hungary																	
1983–1984	0.5	0.36	1.26	0.29	0.32	0.21	0.89	0.25	1.09								
1985–1989	3.4	1.19	2.81	0.99	1.70	0.50	1.43	0.61	1.72	0.00				0.05			
1990–1994	4.0	1.58	3.46	1.06	2.92	0.73	1.84	0.84	2.74	0.01	0.02	0.05	0.18	0.11	0.26	0.57	0.93
Japan																	
1975–1979	7.0	2.02	7.21	6.11	14.1	2.02	6.99	1.96	2.32	0.02				0.18			
1980–1984	11.8	5.44	13.2	9.22	30.7	2.60	5.65	2.32	3.33	0.02				0.16			
1985–1989	16.2	9.22	18.6	12.1	33.5	2.07	3.63	1.80	2.76	0.01				0.12			
1990–1994	20.2	10.88	22.6	12.7	26.4	1.30	2.42	1.17	2.08	0.00	0.02	0.07					
Netherlands																	
1975–1979	1.0	0.37	0.60		4.10	4.10	11.0	6.89		0.14				0.44			
1980–1984	1.0	0.39	0.96		3.58	3.58	9.24	3.75		0.06				0.30			
1985–1989	1.0	0.39	1.14		2.83	2.83	7.21	2.48		0.02				0.15			
1990–1994	2.0	0.40	1.77	1.25	2.59	1.30	6.47	1.47	2.07	0.00	0.02	0.09	0.34	0	0.15	0.51	0.92
Peru 1994	1.0		0.03	0.03	0.02	0.02		0.45	0.52	0	0	0	0.03				
Slovakia																	
1990–1994	4.0	1.31	1.39	1.39	2.74	0.68	2.09	1.97	1.97	0.00	0.02	0.12	0.45	0.02	0.13	0.49	0.90
Slovenia																	
1990–1994	1.0	0.48	0.69	0.69	1.40	1.40	2.92	2.04	2.04	0.01	0.07	0.13	0.41	0.10	0.27	0.59	0.92

Table 7 (continued)

Country / area and period	*Average number of reactors over the period*	*Average annual energy generated (GW a)*	*Monitored workers (thousands)*	*Measurably exposed workers (thousands)*	*Annual collective effective dose*			*Average annual effective dose (mSv)*		*Distribution ratio (number of workers)*				*Distribution ratio (collective dose)*			
					Total (man Sv)	*Average per reactor (man Sv)*	*Average per unit energy generated (man Sv per GW a)*	*Monitored workers*	*Measurably exposed workers*	NR_{15}	NR_{10}	NR_5	NR_1	SR_{15}	SR_{10}	SR_5	SR_1
South Africa																	
1984	2.0	0.45	1.72	0.08	0.12	0.06	0.27	0.07	1.45	0.00				0.29			
1985–1989	2.0	0.96	1.72	0.59	1.61	0.81	1.68	0.94	2.75	0.01				0.18			
1990–1994	2.0	1.06	1.79	0.77	2.07	1.03	1.95	1.15	2.70	0.01	0.03	0.07	0.23	0.13	0.31	0.60	0.93
Spain [d]																	
1975–1979	1.0	0.13	0.22		2.60	2.60	20.7	11.7									
1980–1984	2.6	0.67	1.51		6.76	2.60	10.1	4.21									
1985–1989	5.6	3.25	5.30	3.81	17.7	3.17	5.45	3.35	4.65								
1990–1994	7.0	5.01	6.85	4.53	12.9	1.85	2.58	1.88	2.46	0.01	0.03	0.09	0.31	0.13	0.30	0.57	092
Sweden																	
1975–1979	1.0	0.47		0.62	1.52	1.52	3.28		2.46	0.03				0.24			
1980–1984	2.2	0.87		0.97	3.58	1.63	4.10		3.68	0.03				0.27			
1985–1989	3.0	1.93		1.82	4.80	1.60	2.49		2.65	0.03				0.19			
1990–1994	3.0	2.13			2.70	0.90	1.27							0.19			
Switzerland																	
1975–1979	2.2	0.71	0.63		4.16	1.89	5.83	6.64									
1980–1984	3.0	1.44	1.49		7.46	2.49	5.20	5.01									
1985–1989	3.0	1.44	1.67		6.60	2.20	4.58	3.95									
1990–1994	3.0	1.50	2.15		4.11	1.37	2.74	1.91		0.01	0.04	0.13	0.37	0.10	0.26	0.60	0.92
United States [e]																	
1975–1979	34.2	16.2	38.8	22.8	147	4.31	9.13	3.80	6.47	0.09				0.57			
1980–1984	46.8	22.1	83.1	51.0	276	5.89	12.5	3.32	5.41	0.08				0.53			
1985–1989	63.0	37.4	109.2	61.4	225	3.58	6.02	2.06	3.67	0.04				0.36			
1990–1994	72.6	51.5	114.1	58.0	154	2.12	2.99	1.35	0.31	0.00	0.03	0.09	0.27	0.01	0.13	0.42	0.91
USSR																	
1978–1979	7.5	1.7	3.2		19.4	2.59	11.2	6.14									
1980–1984	12.8	3.8	6.6		32.8	2.56	8.66	4.99									
1985–1987	22.0	8.7	12.3		57.1	2.60	6.55	4.63									
(Russian Fed.)																	
1985–1989	22.0	8.7	12.3		57.1	2.60	6.55	4.63									
1990–1994			10.5		29.2												

Table 7 (continued)

Country / area and period	*Average number of reactors over the period*	*Average annual energy generated (GW a)*	*Monitored workers (thousands)*	*Measurably exposed workers (thousands)*	*Annual collective effective dose*			*Average annual effective dose (mSv)*		*Distribution ratio (number of workers)*				*Distribution ratio (collective dose)*			
					Total (man Sv)	*Average per reactor (man Sv)*	*Average per unit energy generated (man Sv per GW a)*	*Monitored workers*	*Measurably exposed workers*	NR_{15}	NR_{10}	NR_5	NR_1	SR_{15}	SR_{10}	SR_5	SR_1
Total [f]																	
1975–1979	64.4	26.1	60.9		212	3.29	8.13	3.48		0.09				0.56			
1980–1984	121	56.3	144		451	3.73	8.01	3.14		0.06				0.48			
1985–1989	192	112	219		487	2.53	4.36	2.22		0.03				0.32			
1990–1994	209.3	137	260	140	380	1.82	2.78	1.45	2.61	0.00	0.02	0.08	0.27	0.07	0.21	0.51	0.90
World																	
1975–1979	78	27	63		220	2.8	8.1	3.5		0.09				0.56			
1980–1984	140	56	140		450	3.3	8.0	3.1		0.06				0.48			
1985–1989	220	120	230		500	2.3	4.3	2.2		0.03				0.32			
1990–1994	242	149	310	166	415	1.72	2.78	1.34	2.51	0.00	0.02	0.28	0.27	0.07	0.21	0.51	0.90
BWRs																	
China, Taiwan																	
1981–1984	3.8	1.83	6.32		14.4	3.84	7.85	2.28									
1985–1989	4.0	2.32	6.69		18.2	4.55	7.84	2.72									
1990–1994	4.0	2.39	6.17	4.92	13.56	3.39	5.69	2.20	2.76	0.03	0.06	0.13	0.32	0.37	0.53	0.73	0.95
Finland																	
1978–1979	1.0	0.21	1.44	0.29	0.12	0.12	0.55	0.08	0.40								
1980–1984	2.0	1.02	1.61	0.88	0.87	0.44	0.86	0.54	0.99	0.00				0.00			
1985–1989	2.0	1.33	1.92	1.14	1.80	0.90	1.36	0.94	1.59	0.00				0.03			
1990–1994	2.0	1.33	2.12	1.18	1.87	0.94	1.41	0.88	1.59	0.00	0.01	0.04	0.23	0.02	0.14	0.37	0.85
Germany [c]																	
1975–1979	3.0	0.72	3.74		19.9	6.64	27.8	5.33									
1980–1984	4.4	2.12	10.2		33.4	7.59	15.7	3.28									
1985–1989	7.0	5.68	12.4		19.4	2.78	3.42	1.56									
1990–1994	7.0	4.82			15.6	2.23	3.24										
India																	
1980–1984	2.0	0.20	3.35	3.30	38.0	19.0	189	11.4	11.5	0.24							
1985–1989	2.0	0.21	2.69	2.56	23.2	11.6	113	8.63	9.06	0.16							
Japan																	
1975–1979	7.8	2.30	18.2	17.7	72.9	9.35	31.6	4.01	4.12	0.07				0.34			
1980–1984	13.0	6.24	27.4	18.9	91.4	7.03	14.6	3.34	4.83	0.06				0.34			
1985–1989	18.4	10.6	34.8	20.7	63.6	3.46	6.02	1.83	3.07	0.02				0.20			
1990–1994	23.4	13.5	39.6	20.6	44.3	1.89	3.30	1.12	2.15	0.01	0.01	0.04					

Table 7 (continued)

Country / area and period	*Average number of reactors over the period*	*Average annual energy generated (GW a)*	*Monitored workers (thousands)*	*Measurably exposed workers (thousands)*	*Annual collective effective dose*			*Average annual effective dose (mSv)*		*Distribution ratio (number of workers)*				*Distribution ratio (collective dose)*			
					Total (man Sv)	*Average per reactor (man Sv)*	*Average per unit energy generated (man Sv per GW a)*	*Monitored workers*	*Measurably exposed workers*	NR_{15}	NR_{10}	NR_5	NR_1	SR_{15}	SR_{10}	SR_5	SR_1
Mexico																	
1990–1994	1.0	0.49			4.64	4.64	9.40										
Netherlands																	
1975–1979	1.0	0.05	0.28		2.31	2.31	49.2	8.38		0.20				0.24			
1980–1984	1.0	0.05	0.47		2.24	2.24	48.1	4.81		0.11				0.27			
1985–1989	1.0	0.05	0.56		1.62	1.62	32.9	2.87		0.04				0.19			
Spain [d]																	
1975–1979	1.0	0.32	0.62		5.36	5.36	16.8	8.60									
1980–1984	1.2	0.27	0.97		7.85	6.54	29.2	8.08									
1985–1989	2.0	1.09	2.66	2.06	10.1	5.05	9.26	3.80	4.90								
1990–1994	2.0	1.20	2.87	2.24	7.74	3.87	6.43	2.70	3.01	0.01	0.04	0.15	0.47	0.05	0.22	0.57	0.95
Sweden																	
1975–1979	4.6	1.64		2.09	5.98	1.3	3.65		2.86	0.03				0.24			
1980–1984	6.6	3.46		3.13	8.22	1.25	2.38		2.63	0.03				0.27			
1985–1989	9.0	5.64		3.71	10.7	1.19	1.89		2.88	0.03				0.19			
1990–1994	9.0	5.70			15.8	1.76	2.77										
Switzerland																	
1990–1994	2.0	1.18	2.58		3.97	1.99	3.36	1.54		0.01	0.02	0.09	0.33	0.06	0.21	0.53	0.91
United States [e]																	
1975–1979	22.8	9.37	33.3	19.9	156	6.83	16.6	4.68	7.84	0.06				0.65			
1980–1984	26.2	10.4	53.3	35.1	268	10.2	25.7	5.03	7.63	0.08				0.63			
1985–1989	32.2	14.7	77.2	40.5	181	5.63	12.3	2.35	4.48	0.03				0.43			
1990–1994	37.0	21.5	76.6	40.1	131	3.54	6.08	1.71	3.27	0.00	0.04	0.12	0.30	0.14	0.28	0.62	0.94
Total																	
1975–1979	40.6	14.3	55.9		262	6.46	18.1	4.69		0.07				0.61			
1980–1984	59.0	25.2	102		454	7.69	18.0	4.47		0.08				0.55			
1985–1989	77.6	41.6	139		330	4.25	7.93	2.38		0.03				0.36			
1990–1994	87.4	52.1	160	87.0	238	2.73	4.58	1.56		0.01	0.04	0.12	0.31	0.13	0.33	0.63	0.94
World																	
1975–1979	51.2	15.3	59.2		279	5.45	18.3	4.71		0.07				0.61			
1980–1984	64.6	25.1	102		454	7.00	18.0	4.47		0.08				0.55			
1985–1989	83.8	41.8	139		331	3.96	7.94	2.38		0.03				0.36			
1990–1994	90.0	50.4	160	87.0	240	2.67	4.76	1.57	2.86	0.00	0.04	0.12	0.31	0.13	0.33	0.63	0.94

Table 7 (continued)

Country / area and period	*Average number of reactors over the period*	*Average annual energy generated (GW a)*	*Monitored workers (thousands)*	*Measurably exposed workers (thousands)*	*Annual collective effective dose*			*Average annual effective dose (mSv)*		*Distribution ratio (number of workers)*				*Distribution ratio (collective dose)*			
					Total (man Sv)	*Average per reactor (man Sv)*	*Average per unit energy generated (man Sv per GW a)*	*Monitored workers*	*Measurably exposed workers*	NR_{15}	NR_{10}	NR_5	NR_1	SR_{15}	SR_{10}	SR_5	SR_1
HWRs																	
Argentina																	
1975–1979	1.0	0.26	0.43		4.52	4.52	17.2	10.5		0.26				0.73			
1980–1984	1.4	0.32	0.77		8.04	5.74	25.2	10.5		0.27				0.79			
1985–1989	2.0	0.61	1.06		12.6	6.29	20.8	11.9		0.29				0.80			
1990–1994	2.0	0.87	1.47	1.26	12.0	6.01	13.8	8.17	9.54	0.20	0.27	0.41	0.66	0.65	0.77	0.90	0.99
Canada																	
1975–1979	8.4	2.45	5.65	2.62	24.0	2.85	9.77	4.24	9.15	0.11				0.70			
1980–1984	13	4.53	9.27	3.54	20.1	1.57	4.43	2.16	5.67	0.05				0.49			
1985–1989	18	8.03	11.0	4.61	16.7	0.94	2.07	1.51	3.61	0.02				0.23			
1990–1994	22.0	8.63	15.0	5.05	15.9	0.72	1.66	1.06	3.15	0.01	0.02	0.07	0.22	0.11	0.22	0.59	0.93
Czechoslovakia [a]																	
1975–1979	1.0		0.85	0.65	4.61	4.61		5.42	7.03	0.11				0.58			
1980–1984	1.0		0.51	0.36	0.77	0.77		1.51	2.13	0.02				0.22			
1985–1989	1.0		0.54	0.31	0.88	0.88		1.62	2.83	0.02				0.24			
Japan																	
1990–1994	1.0	0.11	1.79	1.11	3.28	3.28	29.06	1.84	2.96	0.01	0.04	0.12	0.36	0.09	0.29	0.61	0.94
Pakistan																	
1990–1994	1.0	0.48	0.65	0.54	1.87	1.87	3.92	2.89	3.23	0.02	0.07	0.20	0.51	0.14	0.32	0.65	0.95
Rep. of Korea																	
1983–1984	1.0	0.41	0.72		0.65	0.65	1.58	0.90									
1985–1989	1.0	0.59	0.81		1.13	1.13	1.91	1.40									
Total																	
1975–1979	9.40	2.71	6.08		28.5	3.03	10.5	4.68		0.12				0.71			
1980–1984	16.6	5.13	12.8		40.9	2.47	7.97	3.20		0.08				0.58			
1985–1989	25.0	9.61	17.3		59.0	2.36	6.14	3.41		0.07				0.48			
1990–1994	24.0	9.25	16.5	6.31	27.9	1.16	3.02	1.69	4.43	0.02	0.04	0.10	0.26	0.34	0.46	0.72	0.96
World																	
1975–1979	12	3.1	6.8		32	2.6	11	4.8		0.12				0.71			
1980–1984	19	5.7	14		46	2.4	8.0	3.2		0.07				0.58			
1985–1989	26	9.8	18		60	2.3	6.2	3.4		0.07				0.48			
1990–1994	31.2	11.6	20	7.90	35	1.1	3.0	1.74	4.35	0.02	0.04	0.10	0.26	0.34	0.46	0.72	0.96

Table 7 (continued)

Country / area and period	*Average number of reactors over the period*	*Average annual energy generated (GW a)*	*Monitored workers (thousands)*	*Measurably exposed workers (thousands)*	*Annual collective effective dose*			*Average annual effective dose (mSv)*		*Distribution ratio (number of workers)*				*Distribution ratio (collective dose)*			
					Total (man Sv)	*Average per reactor (man Sv)*	*Average per unit energy generated (man Sv per GW a)*	*Monitored workers*	*Measurably exposed workers*	NR_{15}	NR_{10}	NR_5	NR_1	SR_{15}	SR_{10}	SR_5	SR_1
GCRs																	
France																	
1990–1994	2.0	0.32			0.58	0.29	1.78										
Japan																	
1979	1.0	0.1	1.59	0.81	1.0	1.0	10	0.63	1.23	0.00							
1980–1984	1.0	0.1	2.13	0.95	1.0	1.0	10	0.47	1.05	0.00				0.02			
1985–1989	1.0	0.1	2.01	0.84	1.0	1.0	10	0.50	1.19	0.00				0.01			
1990–1994	1.0	0.08	1.74	0.54	0.42	0.42	4.99	0.24	0.78	0.00	0.00	0.01					
Spain																	
1975–1979	1.0	0.37	0.07		0.30	0.30	0.80	3.98									
1980–1984	1.0	0.36	0.18		0.37	0.37	1.02	2.08									
1985–1989	1.0	0.33	0.25	0.13	0.28	0.28	0.85	1.12	2.18								
1990–1994																	
United Kingdom																	
1975–1979	30.0	3.40	8.56		24.5	0.82	7.20	2.86		0.02							
1980–1984	32.0	4.40	18.0		26.4	0.82	6.00	1.46		0.00							
1985–1989	37.0	6.09	25.4		19.5	0.52	3.20	0.77		0.00							
1990–1991	36.0	7.72	26.4		15.0	0.42	1.94	0.57		0.00							
Total																	
1975–1979	31.2	3.79	8.95		25.0	0.80	6.59	2.80		0.02							
1980–1984	34.0	4.86	20.3		27.8	0.82	5.72	1.37		0.01							
1985–1989	39.2	6.52	27.6		20.8	0.53	3.19	0.75		0.00				0.01			
1990–1994	39	8.14			15.9	0.41	1.96										
World																	
1975–1979	40	5.4	13		36.0	0.90	6.6	2.8									
1980–1984	41	6.0	25		34.0	0.84	5.8	1.4									
1985–1989	44	7.4	31		24.0	0.54	3.2	0.75									
1990–1994	37.6	8.36	30		16.4	0.44	1.96	0.54									
LWGRs																	
Lithuania [g]																	
1990–1994	2				16.06	8.03											

Table 7 (continued)

Country / area and period	*Average number of reactors over the period*	*Average annual energy generated (GW a)*	*Monitored workers (thousands)*	*Measurably exposed workers (thousands)*	*Annual collective effective dose*			*Average annual effective dose (mSv)*		*Distribution ratio (number of workers)*				*Distribution ratio (collective dose)*			
					Total (man Sv)	*Average per reactor (man Sv)*	*Average per unit energy generated (man Sv per GW a)*	*Monitored workers*	*Measurably exposed workers*	NR_{15}	NR_{10}	NR_5	NR_1	SR_{15}	SR_{10}	SR_5	SR_1
Russian Fed. [h]																	
1990–1994	10.4				100.6	9.67											
Total																	
1990–1994	12.4				116.7	9.40											
World																	
1978–1979	12	4.35	5.37		35.6	2.97	8.18	6.64									
1980–1984	16.2	7.50	9.80		62.2	3.84	8.30	6.35									
1985–1987	20	10.4	13.1		173	8.67	16.7	13.2									
1990–1994	20	9.38			190	9.40	20.3										

a The data are annual averages over the periods indicated.
b Data for 1985–1989 are for Czechoslovakia.
c Data for 1985–1989 cover the Federal Republic of Germany and German Democratic Republic. Within the period 1990–1994, the data for 1990 relate to the Federal Republic of Germany.
d Calculation of distribution ratios based on data from 1993 and 1994.
e Calculation of SR distribution ratios based on data from 1993 and 1994.
f Excludes data from Russian Federation.
g Data was provided by ISOE database [L5].
h Data taken from Rosenergoatom Concern Annual Report [R2].

Table 8
Summary of worldwide exposures from reactor operation [a]

Reactor type	*Average number of reactors*	*Average annual energy generated* [b] *(GW a)*	*Monitored workers* [c] *(thousands)*	*Average annual collective effective dose* [d] *(man Sv)*	*Collective effective dose per reactor (man Sv)*	*Collective effective dose per unit energy generated (man Sv per GW a)*	*Average annual effective dose to monitored workers (mSv)*	*Annual average dose to measurably exposed workers (mSv)*	*Average annual value of* NR_{15} [e]	*Average annual value of* SR_{15}
1975–1979										
PWR	78	27	63	220	2.8	8.1	3.5		0.085	0.56
BWR	51	15	59	280	5.45	18	4.7		0.066	0.61
HWR	12	3.1	6.8	32	2.6	11	4.8		0.12	0.71
LWGR [f]	12	4.4	5.4	36	2.97	8.2	6.6			
GCR	40	5.4	13	36	0.90	6.6	2.8		0.020	
HTGR [g]	1	0.03	1.2	0.03	0.03	0.90	0.03			
Total	190	55	150	600	3.2	11	4.1		0.078	0.60
1980–1984										
PWR	140	56	140	450	3.3	8.0	3.1		0.061	0.48
BWR	65	25	100	450	7.00	18	4.5		0.079	0.55
HWR	19	5.7	14	46	2.4	8.0	3.2		0.073	0.58
LWGR	16	7.5	9.8	62	3.82	8.3	6.4			
GCR	41	6.0	25	34	0.82	5.8	1.4		0.005	
FBR	4	0.50	1.4	0.61	0.15	1.2	0.44			
HTGR	1	0.07	1.2	0.02	0.02	0.24	0.01			
Total	280	100	290	1000	3.6	10	3.5		0.069	0.52
1985–1989										
PWR	220	120	230	500	2.3	4.3	2.2		0.034	0.32
BWR	84	42	140	330	3.96	7.9	2.4		0.026	0.36
HWR	26	10	18	60	2.3	6.2	3.4		0.066	0.48
LWGR [h]	20	10	13	170	8.67	17	13			
GCR	44	7.4	31	24	0.54	3.2	0.75		0.0002	0.01
FBR [i]	5	0.73	2.1	1.0	0.21	1.4	0.48			
HTGR	1	0.03	0.78	0.10	0.10	3.3	0.12			
Total	400	190	430	1100	2.8	5.9	2.5		0.033	0.34

Table 8 (continued)

Reactor type	*Average number of reactors*	*Average annual energy generated* [b] *(GW a)*	*Monitored workers* [c] *(thousands)*	*Average annual collective effective dose* [d] *(man Sv)*	*Collective effective dose per reactor (man Sv)*	*Collective effective dose per unit energy generated (man Sv per GW a)*	*Average annual effective dose to monitored workers (mSv)*	*Annual average dose to measurably exposed workers (mSv)*	*Average annual value of* NR_{15} [e]	*Average annual value of* SR_{15}
1990–1994										
PWR	242	149	310	415	1.7	2.8	1.3	2.5	0.00	0.07
BWR	90	50	160	240	2.7	4.8	1.6	2.9	0.00	0.13
HWR	31	12	20	35	1.1	3.0	1.7	4.4	0.02	0.34
LWGR	20	9.4		190	9.4	20.3				
GCR	38	8.4	30	16	0.4	2.0	0.5			
Total	421	230	530	900	2.1	3.9	1.4	2.7	0.00	0.08

a The data are annual values averaged over the respective five-year periods and are, in general, quoted to two significant figures.
b Values in parentheses are the percentage contributions, rounded to the nearest per cent, made by that reactor type to the total energy generated.
c Values in parentheses are the percentage contributions, rounded to the nearest per cent, made by that reactor type to the total number of monitored workers.
d Values in parentheses are the percentage contributions, rounded to the nearest per cent, made by that reactor type to the total collective effective dose.
e The values of the ratios, NR_{15} and SR_{15} are only indicative of worldwide levels. Data on these ratios are not available from all countries, and the tabulated values are averages of those data reported.
f Averages of 1978 and 1979 tabulated and assumed representative of whole period in absence of data for earlier years.
g Includes data for Fort St. Vrain only; insufficient data to extrapolate to other prototype HTGRs.
h Averages of 1985–1987 tabulated and assumed representative of whole period in absence of data for later years in period.
i Averaged over 1986, 1987 and 1989, as data for other years in period were unavailable.

Table 9
Collective effective doses to workers at reactors during replacement of steam generators
[O5]

Country	*Reactor*	*Replacement year*	*Number of loops replaced*	*Collective effective dose (man Sv)*	
				Per replacement	*Per loop*
Belgium	Doel 3	1993	3	1.96	0.65
France	Dampierre 1	1990	3	2.13	0.71
	Bugey 5	1993/1994	3	1.55	0.52
	Gravelines 1	1994	3	1.45	0.48
Germany	Obrigheim	1983	2	6.90	3.45
Japan	Mihama 2	1994	2	1.46	0.73
	Takahama 2	1994	3	1.49	0.50
Sweden	Ringhals 2	1989	3	2.90	0.97
Switzerland	Beznau 1	1993	2	1.10	0.55
United States	Surry 2	1979	3	21.4	7.14
	Surry 1	1980	3	17.6	5.86
	Turkey Point 3	1981	3	21.5	7.17
	Turkey Point 4	1982	3	13.1	4.35
	Point Beach 1	1983	2	5.90	2.95
	H.B. Robinson 2	1984	3	12.1	4.02
	D.C. Cook 2	1988	4	5.61	1.40
	Indian Point	1989	4	5.41	1.35
	Palisades	1990	3	4.87	1.62
	Millstone 2	1992	3	6.70	2.23
	North Anna 1	1993	3	2.40	0.80

Table 10
Exposures to workers from fuel reprocessing [a]
Data from UNSCEAR Survey of Occupational Exposures

Country / area and period	Average annual amount of fuel processed (kt U)	Electrical energy equivalent (GW a)	Monitored workers (thousands)	Measurably exposed workers (thousands)	Annual collective effective dose			Average annual effective dose (mSv)		Distribution ratio [b] (number of workers)				Distribution ratio (collective dose)			
					Total (man Sv)	Average per unit fuel generated (man Sv per kt)	Average per unit energy generated (man Sv per GW a)	Monitored workers	Measurably exposed workers	NR_{15}	NR_{10}	NR_5	NR_1	SR_{15}	SR_{10}	SR_5	SR_1
France																	
1975–1979	0.360	1.46	4.35	2.97	12.8			2.94	4.31	0.06				0.29			
1980–1984	0.375	3.87	6.70	3.89	14.1			2.10	3.62	0.01				0.11			
1985–1989	0.434	8.85	9.28	3.86	12.5			1.35	3.25	0.01				0.12			
1990–1994			13.0	3.31	4.72			0.36	1.43	0.00	0.00	0.01	0.26				
India																	
1981–1984			1.48	1.27	6.76			4.57	5.33	0.087				0.459			
1985–1989			1.66	1.32	5.53			3.34	4.19	0.046				0.308			
1990-1994 [c]			1.66	1.32	5.53												
Japan																	
1975–1979	0.010		0.84		0.38	38		0.44		0							
1980–1984	0.030		1.37		1.23	41		0.89		0.000							
1985–1989	0.052		1.87		1.83	35.2		0.98		0.01							
1990–1994	0.074	1.4	2.58	0.71	0.82	11.1	0.60	0.32	1.15	0.00	0.00	0.01	0.08	0.03	0.03	0.13	0.64
Netherlands																	
1990–1994			0.08	0.04	0.03			0.39	0.75	0.00	0.00	0.01	0.12	0.00	0.00	0.07	0.66
Russian Fed.																	
1990–1994			12.0	11.5	33.9			2.82	2.96					0.19			
United Kingdom																	
1977–1979	0.715	2.17	5.61		46.6	65	21.5	8.31		0.193							
1980–1984	0.970	2.94	6.62		40.1	41	13.6	6.05		0.143							
1985–1989	0.887	2.69	7.22		29.4	33	11.0	4.07		0.10							
1990–1994			10.2		20.7			2.03		0.00	0.03	0.12		0.08			
United States																	
1975–1979			2.65	2.05	10.8			4.06	5.27								
1980–1984			2.95	2.06	7.43			2.51	3.61								
1985–1989			3.21	1.78	4.89			1.52	2.74								
1990-1994 [d]			5.61	1.99	1.64			0.30	0.82								

Table 10 (continued)

Country / area and period	*Average annual amount of fuel processed (kt U)*	*Electrical energy equivalent (GW a)*	*Monitored workers (thousands)*	*Measurably exposed workers (thousands)*	*Annual collective effective dose*			*Average annual effective dose (mSv)*		*Distribution ratio [b] (number of workers)*				*Distribution ratio (collective dose)*			
					Total (man Sv)	*Average per unit fuel generated (man Sv per kt)*	*Average per unit energy generated (man Sv per GW a)*	*Monitored workers*	*Measurably exposed workers*	NR_{15}	NR_{10}	NR_5	NR_1	SR_{15}	SR_{10}	SR_5	SR_1
World [e]																	
1975–1979			7.5		53			7.07									
1980–1984			9.4		46			4.89									
1985–1989			17.0		36			2.46		0.047							
1990–1994			45	24	67			1.49	2.79					0.13			

a Data are annual averages over the indicated period.
b These values are based on the monitored workforce, and if not available on the measurably exposed workers.
c No data was reported for India for 1990–1994, therefore the Committee has assumed that data for the previous period are still a valid approximation.
d Reprocessing at United States Department of Energy facilities are mainly associated with defense activities rather than commercial fuel reprocessing [D4].
e Great care should be taken when trying to compare different time periods. In particular the world estimates for the time periods from 1975 to 1989 were based on the French and United Kingdom operations, as the other major contributor, the United States was considered to be more concerned with defense activities. The data for 1990–1994 covers all contributions and in particular a contribution from the Russian Federation which accounts for some 50% of the annual collective effective dose.

Table 11
Exposures to workers from research in the nuclear fuel cycle [a]
Data from UNSCEAR Survey of Occupational Exposures

Country / area	*Period*	*Monitored workers* (thousands)	*Measurably exposed workers* (thousands)	*Annual collective effective dose* (man Sv)	*Average annual effective dose (mSv)*		*Distribution ratio (number of workers)*				*Distribution ratio (collective dose)*			
					Monitored workers	*Measurably exposed workers*	NR_{15}	NR_{10}	NR_5	NR_1	SR_{15}	SR_{10}	SR_5	SR_1
Argentina	1975–1979	0.2	0.01	0.2	1.0	20								
	1980–1984	0.2	0.01	0.17	0.85	17								
	1985–1989	0.13	0.02	0.07	0.54	3.9								
	1990–1994	0.11	0.08	0.08	0.76	1.03	0.00	0.00	0.03	0.20	0.00	0.05	0.23	0.75
Canada [b]	1975–1979	4.49	3.94	13.5	2.95	3.36	0.01				0.44			
	1980–1984	4.56	4.30	11.1	2.43	2.57	0.04				0.41			
	1985–1989	4.20	3.97	6.1	1.45	1.54	0.03				0.40			
	1990–1994	4.12	3.25	6.0	1.46	1.85	0.02	0.04	0.07	0.25	0.23	0.39	0.54	0.78
Chile [c]	1975–1979	0.02	0.02	0.04	2.41	2.41	0.01				0.03			
	1980–1984	0.03	0.03	0.05	2.00	2.00	0.03				0.11			
	1985–1989	0.05	0.05	0.06	1.23	1.23	0.02				0.06			
China	1990–1994	1.27	0.90	1.0	0.79	1.10	0.01	0.01	0.03	0.14	0.26	0.35	0.50	0.77
Czech Republic [d]	1985–1979	0.36		0.17	0.48									
	1980–1984	0.34		0.18	0.52									
	1985–1989	0.36		0.13	0.38									
	1990–1994	0.48		0.69	1.44									
Denmark [e]	1990–1994	1.10	0.20	0.28	0.26	1.45	0.00	0.00	0.01	0.07	0.00	0.02	0.25	0.82
Finland	1975–1979		0.01	0.01		1.58								
	1980–1984		0.00	0.01		2.58								
	1985–1989		0.01	0.05		3.47					0.25			
	1990–1994	0.02	0.00	0.00	0.11	0.64	0.00	0.00	0.00	0.04	0.00	0.00	0.00	0.33
France	1975–1979	20.9	3.19	9.32	0.44	2.92	0.01							
	1980–1984	21.0	2.86	8.47	0.40	2.97	0.00							
	1985–1989	19.6	2.48	6.14	0.31	2.47	0.00							
	1990–1994	16.3	1.87	3.68	0.23	1.97	0.00	0.00	0.01	0.11				
Germany [f]	1975–1979	0.71		3.80	5.37									
	1980–1984	0.84		3.04	3.64									
	1985–1989	1.66		1.15	0.69									
Hungary [g]	1977–1979	0.12	0.01	0.01	0.06	1.49								
	1980–1984	0.13	0.01	0.00	0.03	0.83								
	1985–1989	0.12	0.01	0.01	0.07	0.96								

Table 11 (continued)

Country / area	*Period*	*Monitored workers (thousands)*	*Measurably exposed workers (thousands)*	*Annual collective effective dose (man Sv)*	*Average annual effective dose (mSv)*		*Distribution ratio (number of workers)*				*Distribution ratio (collective dose)*			
					Monitored workers	*Measurably exposed workers*	NR_{15}	NR_{10}	NR_{5}	NR_{1}	SR_{15}	SR_{10}	SR_{5}	SR_{1}
India	1980–1984 1985–1989	2.78 3.62	1.97 2.38	6.36 4.65	2.29 1.28	3.23 1.96	0.03 0.01				0.36 0.18			
Indonesia [h]	1975–1979 1980–1984 1985–1989	0.02 0.03 0.10	 0.04 0.10	0.09 0.10 0.09	3.87 2.72 0.95	 3.10 0.95	0.13 0.16 0.03				0.37 0.72 0.47			
Italy	1985–1989 1990–1994	2.44	0.45	0.26	0.11	0.58	0.00				0.01			
Japan [i]	1978–1979 1980–1984 1985–1989 1990–1994	4.12 7.01 9.18 8.15	 1.04	2.13 7.97 7.72 1.53	0.52 1.14 0.84 0.19	 1.48	0.00 0.02 0.01 0.00	 0.00	 0.01	 0.05	 0.01	 0.10	 0.38	 0.83
Netherlands	1990–1994	1.65	0.40	0.12	0.07	0.27	0.00	0.00	0.00	0.01	0.00	0.04	0.06	0.31
Norway [j]	1980–1984 1985–1989 1990–1994	0.68 0.76 0.20	0.14 0.15 0.09	0.53 0.58 0.17	0.77 0.76 0.85	3.76 3.88 1.83	0.01 0.01 0.00	 0.00	 0.04	 0.23	0.34 0.35	 	 	
Republic of Korea [k]	1975–1979 1980–1984 1985–1989	0.25 0.79 0.99	 0.14 0.15	0.12 0.50 0.65	0.46 0.64 0.65	 3.58 4.36	0.00 0.01 0.01							
Russian Fed.	1992–1994		6.74	16.1		2.39	0.02				0.13			
Slovenia	1990–1994	0.02	0.01	0.02	1.10	1.61	0.00	0.00	0.00	0.15	0.00	0.00	0.00	0.14
South Africa	1975–1979 1980–1984 1985–1989 1990–1994	0.25 0.24 0.23 0.05	 0.03	0.12 0.08 0.07 0.02	0.46 0.33 0.34 0.35	 0.72	0.00 0.00 0.00	 0.00	 0.00	 0.10	0.07 0.09 0.00	 0.00	 0.00	 0.44
Sweden	1990–1994	0.45	0.18	0.57	1.26	3.14	0.01	0.03	0.09	0.20	0.22	0.39	0.72	0.94
Thailand	1990–1994	0.03	0.01	0.01	0.47	1.26	0.00	0.00	0.01	0.11	0.00	0.00	0.11	0.63
United Kingdom	1975–1979 1980–1984 1985–1989 1990–1994	8.49 9.00 9.40 5.63	 	37.4 28.2 24.0 5.60	4.40 3.13 2.55 1.00	 	0.09 0.05 0.03							

Table 11 (continued)

Country / area	*Period*	*Monitored workers (thousands)*	*Measurably exposed workers (thousands)*	*Annual collective effective dose (man Sv)*	*Average annual effective dose (mSv)*		*Distribution ratio (number of workers)*				*Distribution ratio (collective dose)*			
					Monitored workers	*Measurably exposed workers*	NR_{15}	NR_{10}	NR_5	NR_1	SR_{15}	SR_{10}	SR_5	SR_1
United States	1975–1979	30.3	14.8	33.0	1.09	2.24								
	1980–1984	28.8	12.7	24.2	0.84	1.90								
	1985–1989	31.7	11.9	19.2	0.60	1.61								
	1990–1994													
Total [l] [m]	1975–1979	63.4		96.3	1.52		0.04				0.42			
	1980–1984	75.5		89.4	1.18		0.02				0.39			
	1985–1989	82.6		66.0	0.80		0.00				0.30			
	1990–1994	46.3	16.4	35.9	0.77	2.18	0.00	0.01	0.02	0.13	0.22	0.36	0.52	0.78
World [n]	1975–1979	120		170	1.4									
	1980–1984	130		150	1.1									
	1985–1989	130		100	0.82			0.01			0.30			
	1990–1994	120	36.0	90	0.78	2.50	0.00	0.01	0.02	0.13	0.22	0.36	0.52	0.78

a Data are annual averages over the periods indicated.
b Data are for research activities carried out by Ontario Hydro and AECL; for 1975–1987, the data contain a component arising from isotope production, which was then undertaken by AECL.
c Includes data for fuel research, a research reactor and radioisotope production.
d The data for 1985–1989 refer to Czechoslovakia.
e Data refer to work at Risø National Laboratory. Activities include research reactor operation, accelerator operation, isotope production, waste handling, research and development, and education.
f The 1975–1989 is from the Federal Republic of Germany and covers only research and prototype reactors.
g Includes only workers employed at the research reactor of the Atomic Energy Institute; some other nuclear fuel cycle research may be carried out at other research and university institutes.
h Comprises data for workers at research reactors.
i Comprises exposures of workers at test and research reactors, the nuclear ship, critical assemblies and at research facilities for nuclear fuel materials.
j Comprises only workers at the Institute of Energy Technology.
k Comprises exposures of workers at TRIGA research reactors and other fuel research facilities.
l Total of reported data. In the total of the monitored workers, the measurably exposed value for the Russian Federation is included.
m The total for measurably exposed has been increased pro rata to take account of countries reporting numbers of monitored workers, but not measurably exposed workers.
n In the absence of better data the values of NR_{15} and SR_{15} for the total reported data have been considered indicative of worldwide levels.

Table 12
Worldwide average annual exposures from the commercial nuclear fuel cycle [a]

Practice	*Monitored workers* [b] *(thousands)*	*Average annual collective effective dose (man Sv)*	*Average annual collective effective dose per unit energy generated (man Sv per GW a)*	*Average annual effective dose to monitored workers*	*Distribution ratio* [c]	
					NR_{15} [d]	SR_{15}
1975–1979						
Mining [e f]	240	1 300	5.7	5.5	0.37	0.69
Milling [e f]	12	120	0.52	10	0.41	0.76
Enrichment [e]	11	5.3	0.02	0.5	0.00	0.00
Fuel fabrication	20	36	0.59	1.8	0.012	0.38 [i]
Reactor operation	150	600	11.0	4.1	0.078 [h]	0.60 [j]
Reprocessing [g]	7.2	53	0.70	7.3	0.16	0.29 [g]
Research	120	170	1.0	1.4	0.035	0.42
Total	560	2 300	20	4.1	0.20	0.63
1980–1984						
Mining [e f]	310	1 600	5.5	5.1	0.30	0.61
Milling [e f]	23	120	0.41	5.1	0.30	0.64
Enrichment [e]	4.3	0.8	0.02	0.2	0.00	0.00
Fuel fabrication	21	21	0.21	1.0	0.002	0.11 [i]
Reactor operation	290	1 000	10.0	3.6	0.069 [h]	0.52 [j]
Reprocessing [g]	9.4	47	0.75	4.9	0.10	0.11 [g]
Research	130	150	1.0	1.1	0.021	0.39
Total	800	3 000	18	3.7	0.16	
1985–1989						
Mining [e f]	260	1 100	4.3	4.4	0.25	0.52
Milling [e f]	18	120	0.44	6.3	0.18	0.43
Enrichment [e]	5.0	0.4	0.02	0.08	0.00	0.00
Fuel fabrication	28	22	0.12	0.78	0.002	0.019 [i]
Reactor operation	430	1 100	5.9	2.5	0.033 [h]	0.34 [j]
Reprocessing [g]	12	36	0.65	3.0	0.064	0.12 [g]
Research	130	100	1.0	0.82	0.011	0.30
Total	880	2 500	12	2.9	0.10	0.42
1990–1994						
Mining [e f]	69 (62)	310	1.72	4.5 (5.0)	0.10	0.32
Milling [e f]	6	20	0.11	3.3	0.00	0.01
Enrichment [e]	13	1	0.02	0.12	0.00	0.00
Fuel fabrication	21 (11)	22	0.1	1.03 (2.0)	0.01	0.11
Reactor operation	530 (300)	900	3.9	1.4 (2.7)	0.00 [h]	0.08
Reprocessing [g k]	45 (24)	67	3.0	1.5 (2.8)	0.00	0.13
Research	120 (36)	90	1.0	0.78 (2.5)	0.01	0.22
Total	800 (450)	1 400	9.8	1.75 (3.1)	0.01	0.11

a The data are annual values averaged over the indicated periods.
b Data in parentheses relate to data for measurably exposed workers.
c The values of the distribution ratios should only be considered indicative of worldwide levels as they are based, in general, on data from far fewer countries than the data for number of workers and collective doses.
d This ratio applies to monitored workers.
e Also include uranium obtained or processed for purposes other than the commercial nuclear fuel cycle.
f For 1985–1989 the data for mining and milling (except for NR and SR) have been modified from those reported by using a conversion factor of 5.6 mSv WLM^{-1} for exposure to radon daughters (10 mSv WLM^{-1} used in the reported data). The ratios NR_{15} and SR_{15} are averages of reported data in which, in general, the previously used conversion factor has been applied. The tabulated ratios are thus strictly for a value of E somewhat less than 15 mSv. The relationship between the reported and revised data is not linear because exposure occurs from other than just inhalation of radon progeny. For 1990–1994 a conversion factor of 5.0 mSv WLM^{-1} for exposure to radon daughters has been used.
g Also includes the reprocessing of some fuel from the defence nuclear fuel cycle.
h Does not include data for LWGRs, FBRs and HTGRs.
i Ratio applies to LWR and HWR fuels only, as data for other fuels are not available; the ratio would be smaller if all fuel types were included.
j Does not include data for GCRs, LWGRs, FBRs and HTGRs.
k In the absence of sufficient data on equivalent electrical energy generated from reporting countries for 1990-1994, the Committee has taken the normalized average annual collective effective per unit energy generated to be the same as that for the previous period.

Table 13
Exposures to workers from medical uses of radiation [a]
Data from UNSCEAR Survey of Occupational Exposures

Country / area	*Period*	*Monitored workers* (thousands)	*Measurably exposed workers* (thousands)	*Annual collective effective dose* (man Sv)	*Average annual effective dose (mSv)*		*Distribution ratio* [b] *(number of workers)*				*Distribution ratio (collective dose)*			
					Monitored workers	*Measurably exposed workers*	NR_{15}	NR_{10}	NR_5	NR_1	SR_{15}	SR_{10}	SR_5	SR_1
Diagnostic radiology														
Argentina	1985–1989 1994	2.20 5.99	0.83 2.28	2.89 9.00	1.31 1.50	3.46 3.96	0.02 0.04	0.04	0.05	0.17	0.56 0.61	0.63	0.69	0.93
Australia [c] [d]	1975–1979 1985–1989 1990–1994	3.22 6.21 8.19	4.42 5.52	1.70 0.37 1.04	0.53 0.059 0.13	0.08 0.19	0.00	0.00	0.00	0.01	0.20	0.22	0.27	0.43
Brazil [e]	1985–1989 1990–1994	3.93 4.29	1.01 0.50	2.99 1.40	0.76 0.33	2.97 2.58	0.01 0.00	0.01	0.01	0.05	0.34 0.35	0.46	0.63	0.91
Bulgaria	1990–1994	2.96	0.30	0.97	0.33	1.51	0.00	0.00	0.00	0.05	0.01	0.02	0.06	0.25
Canada	1975–1979 1980–1984 1985–1989 1990–1994	8.4 9.5 10.7 13.2	4.5 2.0 2.7 2.52	3.23 1.71 1.75 1.35	0.38 0.18 0.16 0.10	0.72 0.87 0.64 0.53	0.00 0.00 0.00 0.00	0.00	0.00	0.02	0.07 0.04 0.03 0.05	0.06	0.11	0.47
China	1985–1989 1990–1994	78.1 12.5	13.3 11.7	143 21.2	1.84 1.70	10.8 1.80	0.03 0.01	0.03	0.05	0.31	0.45 0.25	0.34	0.44	0.78
China, Taiwan Province [f]	1985–1989 1990–1994	3.4 5.10	0.99	1.49 0.74	0.44 0.15	0.75								
Croatia	1990–1994	2.90	1.80	0.50	0.17	0.28								
Cyprus	1990–1994	0.15	0.01	0.15	1.00	1.50	0.01	0.01	0.03	0.28	0.21	0.26	0.38	0.93
Czech Republic [g]	1975–1979 1980–1984 1985–1989 1990–1994	5.08 6.89 8.56 7.71	1.27 2.22 2.66 3.66	3.16 4.48 5.84 6.04	0.62 0.65 0.68 0.78	2.50 2.02 2.21 1.65	0.00 0.00 0.00 0.00	0.00	0.01	0.16	0.18 0.10 0.13 0.06	0.10	0.18	0.71
Denmark [h]	1975–1979 1980–1984 1985–1989 1990–1994	4.28 4.02 3.82 3.72	1.17	1.01 0.64 0.43 0.48	0.24 0.16 0.11 0.13	0.41	0.00 0.00 0.00 0.00	0.00	0.00	0.02	0.02 0.01 0.00	0.01	0.07	0.40
Ecuador [h]	1993–1994	0.66	0.41	0.50	0.77	1.24	0.00	0.01	0.01	0.32				

Table 13 (continued)

Country / area	*Period*	*Monitored workers* (thousands)	*Measurably exposed workers* (thousands)	*Annual collective effective dose* (man Sv)	*Average annual effective dose (mSv)*		*Distribution ratio* [b] *(number of workers)*				*Distribution ratio (collective dose)*			
					Monitored workers	*Measurably exposed workers*	NR_{15}	NR_{10}	NR_5	NR_1	SR_{15}	SR_{10}	SR_5	SR_1
Finland [i] [j]	1975–1979 1980–1984 1985–1989 1990–1994	3.88 4.37 4.82 4.71	0.08 0.29 0.30 0.43	0.58 0.71 0.92 1.14	0.15 0.16 0.19 0.24	6.93 2.43 3.10 2.63	0.00 0.00 0.00 0.00	0.00	0.01	0.05	0.46 0.15 0.28 0.27	0.40	0.58	0.91
France [k]	1975–1979 1980–1984 1985–1989	33.4 49.0 61.8	6.05 6.35	39.7 28.3 20.3	1.19 0.58 0.33	4.67 3.19	0.00 0.00 0.00							
Gabon	1990–1994	0.01		0.00	0.02		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Germany [l]	1980–1984 1985–1989	19.2 20.4	3.12 1.17	2.05 1.68	0.11 0.09	0.66 1.44					0.08 0.11			
Greece	1990–1994	4.07	0.97	3.74	0.92	3.86	0.01	0.02	0.04	0.13	0.44	0.55	0.72	0.94
Hungary	1975–1979 1980–1984 1985–1989 1990–1994	5.96 7.49 7.26 6.76	1.22 1.01 0.98 0.65	2.32 1.61 1.49 0.71	0.39 0.22 0.21 0.10	1.90 1.60 1.53 1.09	0.00 0.00 0.00 0.00	0.00	0.00	0.03	0.11 0.09 0.08 0.04	0.06	0.17	0.67
Iceland [h] [j]	1990–1994	0.44	0.13	0.12	0.26	0.48	0.00	0.00	0.01	0.06	0.13	0.26	0.35	0.69
India	1975–1979 1980–1984 1985–1989 1990–1994	6.50 8.00 10.4 10.7	3.64 3.97 5.42 5.59	3.75 2.76 3.54 2.58	0.58 0.35 0.34 0.24	1.03 0.70 0.65 0.42	0.00 0.00 0.00 0.00	0.00	0.01	0.05	0.21 0.15 0.14 0.12	0.18	0.30	0.68
Indonesia	1975–1979 1980–1984 1985–1989	0.98 1.84 2.30	0.94 1.76 2.19	1.59 2.94 3.84	1.62 1.60 1.67	1.70 1.68 1.75	0.00 0.00 0.00				0.02 0.00 0.02			
Ireland	1985–1989 1991–1994	1.46 1.43	0.12 0.15	0.55 0.09	0.38 0.06	4.69 0.60	0.00	0.00	0.00	0.01	0.00	0.03	0.11	0.48
Kuwait	1992–1994	0.48	0.09	0.17	0.36	1.56	0.00	0.00	0.00	0.01	0.18	0.21	0.30	0.60
Myanmar	1990–1994	0.03	0.03	0.02	0.62	0.63	0.00	0.00	0.00	0.04				
Netherlands	1990–1994	9.82	4.24	7.01	0.71	1.64	0.01	0.02	0.03	0.10	0.34	0.47	0.64	0.87
Norway [m]	1990–1992	2.92	0.98	2.29	0.78	2.32	0.01	0.01	0.04	0.14				
Pakistan	1990–1994	0.64	0.62	2.30	3.60	3.99	0.07	0.09	0.15	0.40	0.60	.068	0.79	0.93

Table 13 (continued)

Country / area	*Period*	*Monitored workers* (thousands)	*Measurably exposed workers* (thousands)	*Annual collective effective dose* (man Sv)	*Average annual effective dose (mSv)*		*Distribution ratio* [b] *(number of workers)*				*Distribution ratio (collective dose)*			
					Monitored workers	*Measurably exposed workers*	NR_{15}	NR_{10}	NR_5	NR_1	SR_{15}	SR_{10}	SR_5	SR_1
Peru	1980–1989 1985–1989 1994	1.37 1.48 1.90	1.59	4.95 5.10 4.94	3.61 3.45 2.60	3.10	0.06	0.09	0.13	0.42				
Slovakia	1990–1994	3.39	0.52	0.97	0.28	1.87	0.00	0.00	0.01	0.07	0.13	0.20	0.37	
Slovenia	1993–1994	1.58	1.23	0.61	0.38	0.49	0.00	0.00	0.00	0.06	0.02	0.02	0.08	0.33
Spain	1985–1989 1990–1994	34.3	30.9	25.9	0.76	0.84	0.00				0.12			
Sri Lanka	1990–1994	0.24	0.07	0.12	0.50	1.62	0.00	0.00	0.01	0.07	0.20	0.22	0.32	0.68
Syrian Arab Republic	1990–1994	0.80	0.07	2.42	3.03	4.4	0.00	0.00	0.00	0.01	0.00	0.00	0.01	0.12
Thailand	1990–1994	3.80	1.27	0.73	0.19	0.58	0.00	0.00	0.01	0.04	0.12	0.21	0.35	0.72
United Kingdom [n]	1991	13.7		1.40	0.10									
United Rep. of Tanzania	1990–1994	0.41	0.41	1.90	4.62	4.74	0.02	0.15	0.49	0.85	0.05	0.40	0.81	0.98
Total reported data [o p]	1975–1979 1980–1984 1985–1989 1990–1994	65.7 104 213 135	54.9	54.8 48.3 194 76.7	0.84 0.47 0.91 0.57	1.40	0.00 0.00 0.02 0.01	0.01	0.02	0.10	0.14 0.08 0.40 0.27	0.35	0.46	0.75
World [q]	1975–1979 1980–1984 1985–1989 1990–1994	630 1060 1350 950 (840)	350 (330)	600 720 760 470 (485)	0.94 0.68 0.56 0.50 (0.57)	1.34 (1.47)	0.00 0.00 0.00 0.00 (0.00)	0.01 (0.01)	0.02 (0.02)	0.09 (0.10)	0.11 0.10 0.22 0.19 (0.19)	0.30 (0.29)	0.44 (0.43)	0.77 (0.76)
Dental radiology														
Argentina	1985–1989	0.07	0.04	0.03	0.46	0.74	0.01				0.42			
Australia [c d]	1975–1979 1985–1989 1990–1994	1.16 3.80 3.88	1.60 1.58	0.02 0.08	0.00 0.02	0.01 0.05	0.00	0.00	0.00	0.00	0.24	0.24	0.31	0.41
Brazil [e]	1990–1994	0.72	0.02	0.11	0.15	5.05	0.00	0.00	0.01	0.02	0.61	0.70	0.79	0.96
Bulgaria	1992	0.20	0	0.04	0.21		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Table 13 (continued)

Country / area	*Period*	*Monitored workers* (thousands)	*Measurably exposed workers* (thousands)	*Annual collective effective dose* (man Sv)	*Average annual effective dose (mSv)*		*Distribution ratio* [b] *(number of workers)*				*Distribution ratio (collective dose)*			
					Monitored workers	*Measurably exposed workers*	NR_{15}	NR_{10}	NR_{5}	NR_{1}	SR_{15}	SR_{10}	SR_{5}	SR_{1}
Canada	1975–1979	13.1	0.97	0.42	0.03	0.44	0.00				0.11			
	1980–1989	19.5	0.94	0.60	0.31	0.64	0.00				0.13			
	1985–1989	24.4	0.94	0.64	0.03	0.68	0.00				0.28			
	1990–1994	26.8	0.20	0.25	0.01	1.24	0.00	0.00	0.00	0.00	0.54	0.62	0.65	0.77
Croatia	1990–1994	0.45	0.03	0.05	0.10	1.67								
Cyprus	1990–1994	0.02	0.01	0.01	0.47	0.94	0.01	0.01	0.01	0.11	0.44	0.44	0.44	0.79
Ecuador [h]	1993–1994	0.08	0.05	0.05	0.66	0.93	0.00	0.00	0.01	0.26				
Finland	1990–1994	0.18	0	0.00	0		0.00	0.00	0.00	0.00				
France [k]	1975–1979	6.17		2.61	0.42		0.00							
	1980–1984	11.2	0.74	2.42	0.22	3.25	0.00							
	1985–1989	16.7	0.86	1.97	0.12	2.31	0.00							
Germany [l] [r]	1985–1989	7.82	0.18	0.39	0.05	2.16	0.00				0.60			
	1990–1994	6.73	0.15	0.21	0.03	1.39	0.00	0.00	0.00	0.00	0.44	0.55	0.58	0.77
Greece	1990–1994	0.03	0.00	0.01	0.20	5.32	0.01	0.01	0.01	0.02	0.63	0.63	0.91	0.94
Hungary	1975–1979	0.24	0.01	0.01	0.06	1.54								
	1980–1984	0.32	0.01	0.01	0.03	1.02								
	1985–1989	0.24	0.00	0.00	0.01	0.90								
Iceland	1990–1994	0.04	0	0	0	0.10	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
India	1975–1979	0.37	0.21	0.17	0.45	0.80	0.00				0.04			
	1980–1984	0.45	0.21	0.17	0.38	0.80	0.00				0.06			
	1985–1989	0.63	0.32	0.24	0.38	0.74	0.00				0.19			
	1990–1994	0.73	0.31	0.11	0.15	0.36	0.00	0.00	0.00	0.03	0.03	0.05	0.15	0.55
Indonesia	1975–1979	0.02	0.02	0.03	1.31	1.31								
	1980–1984	0.15	0.15	0.28	1.84	1.84								
	1985–1989	0.10	0.10	0.15	1.50	1.50	0.00				0.02			
Ireland	1985–1989	0.13	0.00	0.00	0.01	0.30								
	1990–1994	0.97	0.00	0.01	0.00	2.75	0.00	0.00	0.00	0.00	0.00	0.00	0.45	0.55
Italy	1985–1989	1.01	0.39	0.07	0.07	0.19	0.00				0.28			

Table 13 (continued)

Country / area	*Period*	*Monitored workers* (thousands)	*Measurably exposed workers* (thousands)	*Annual collective effective dose* (man Sv)	*Average annual effective dose (mSv)*		*Distribution ratio* [b] *(number of workers)*				*Distribution ratio (collective dose)*			
					Monitored workers	*Measurably exposed workers*	NR_{15}	NR_{10}	NR_5	NR_1	SR_{15}	SR_{10}	SR_5	SR_1
Japan	1975–1979 1980–1984 1985–1989 1990–1994	0.35 1.75 3.53 5.40	0.08 0.20 0.35 0.45	0.13 0.34 0.56 0.57	0.36 0.20 0.16 0.11	1.68 1.69 1.60 1.29	0.00	0.00	0.00	0.03	0.22	0.29	0.40	0.82
Kuwait	1992–1994	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Myanmar	1990–1994	0.00	0.00	0.00	0.75	0.75	0.00	0.00	0.00	0.53				
Netherlands	1990–1994	3.33	0.42	0.13	0.04	0.27	0.00	0.00	0.00	0.00	0.27	0.32	0.39	0.45
Norway	1990–1992	0.07	0.00	0.00	0.01	0.28	0.00	0.00	0.00	0.00				
Pakistan	1994	0.00	0.00	0.00	0.27	2.67	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Slovakia	1990–1994	0.01	0.00	0.00	0.08	0.75	0.00	0.00	0.00	0.03	0.00	0.00	0.00	0.67
Slovenia	1993–1994	0.23	0.14	0.05	0.20	0.34	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.09
South Africa	1975–1979 1980–1984 1985–1989	2.27 2.82 3.33	1.06 0.53 0.37	0.12 1.52 4.49	0.05 0.54 1.35	0.11 2.88 12.2	0.00 0.00				0.64 0.18			
Spain	1985–1989 1990–1994	1.29	1.21	1.56	1.21	1.30	0.01				0.10			
Sweden	1992–1994	0.29		0.01	0.04									
Switzerland [s]	1975–1979 1980–1984 1985–1989 1990–1994	7.09 9.13 10.7 11.0		1.21 0.96 0.26 0.25	0.17 0.11 0.03 0.02		0.00 0.00 0.00 0.00	0.00	0.00	0.00	0.07 0.89 0.02 0.16	0.16	0.20	0.38
Thailand	1990–1994	0.27	0.06	0.03	0.12	0.35	0.00	0.00	0.00	0.01	0.16	0.28	0.28	0.71
United Kingdom [n]	1980–1984 1985–1989 1991	20 20 20		2 2 2	0.1 0.1 0.1									
United States [t]	1975–1979 1980–1984 1985–1989	215 259 307	61	80 60 12	0.37 0.23 0.04	0.20								

Table 13 (continued)

Country / area	*Period*	*Monitored workers* (thousands)	*Measurably exposed workers* (thousands)	*Annual collective effective dose* (man Sv)	*Average annual effective dose (mSv)*		*Distribution ratio [b] (number of workers)*				*Distribution ratio (collective dose)*			
					Monitored workers	*Measurably exposed workers*	NR_{15}	NR_{10}	NR_5	NR_1	SR_{15}	SR_{10}	SR_5	SR_1
Total of reported data [o p]	1975–1979 1980–1984 1985–1989 1990–1994	242 322 391 81.4	5.31	84.5 68.8 18.5 3.97	0.35 0.21 0.05 0.05	0.75	0.00 0.00 0.00 0.00	0.00	0.00	0.00	0.08 0.08 0.12 0.28	0.33	0.40	0.64
World [q]	1975–1979 1980–1984 1985–1989 1990–1994	370 500 480 265 (200)	17.0 (17)	120 93 25 16 (13)	0.32 0.20 0.05 0.06 (0.04)	0.89 (0.77)	0.00 (0.00)	0.00 (0.00)	0.00 (0.00)	0.01 (0.01)	0.24 (0.20)	0.29 (0.24)	0.33 (0.28)	0.56 (0.48)
Nuclear medicine														
Argentina	1985–1989 1990–1994	0.92 0.42	0.25 0.23	0.76 1.14	0.82 2.71	3.08 4.91	0.01 0.05	0.05	0.08	0.34	0.26 0.57	0.59	0.67	0.96
Australia [c d]	1975–1979 1985–1989 1990–1994	0.67 2.72 1.58	1.31 0.86	0.20 0.44 0.64	0.30 0.16 0.41	0.33 0.75	0.00	0.00	0.01	0.14	0.01	0.01	0.09	0.76
Brazil [e]	1985–1989 1990–1994	0.92 0.43	0.25 0.19	0.76 0.67	0.82 1.57	3.08 3.50	0.01 0.02	0.04	0.08	0.24	0.26 0.35	0.49	0.71	0.94
Bulgaria	1990–1994	0.19		0.20	1.03									
Canada	1975–1979 1980–1984 1985–1989 1990–1994	0.57 0.85 1.14 1.42	0.41 0.55 0.83 1.00	1.08 1.53 2.24 1.95	1.90 1.81 1.96 1.37	2.63 2.80 2.71 1.96	0.01 0.00 0.00 0.00	0.00	0.04	0.46	0.13 0.05 0.04 0.01	0.03	0.21	0.91
China	1985–1989	6.08	0.71	9.52	1.57	13.3	0.01				0.27			
China, Taiwan Province	1985–1989 1990–1994	0.38 0.50	0.23	0.10 0.14	0.27 0.29	0.63	0.00	0.00	0.00	0.07	0.07	0.10	0.50	0.96
Croatia	1990–1994	0.06	0.04	0.05	0.80	1.10								
Cuba	1990–1994	0.17	0.17	0.46	2.79	2.79	0.01	0.13	0.27	0.83	0.12	0.21	0.36	0.95
Cyprus	1990–1994	0.01	0.01	0.01	0.67	0.73	0.00	0.00	0.00	0.22	0.00	0.00	0.00	0.59
Czech Republic [g]	1975–1979 1980–1984 1985–1989 1990–1994	0.74 1.08 1.46 0.76	0.22 0.67 0.75 0.70	0.43 0.99 1.26 0.74	0.58 0.92 0.87 0.98	1.83 1.48 1.68 1.05	0.00 0.00 0.00 0.00	0.00	0.01	0.35	0.04 0.03 0.01 0.01	0.04	0.10	0.68

Table 13 (continued)

Country / area	*Period*	*Monitored workers* (thousands)	*Measurably exposed workers* (thousands)	*Annual collective effective dose* (man Sv)	*Average annual effective dose (mSv)*		*Distribution ratio* [b] *(number of workers)*				*Distribution ratio (collective dose)*			
					Monitored workers	*Measurably exposed workers*	NR_{15}	NR_{10}	NR_5	NR_1	SR_{15}	SR_{10}	SR_5	SR_1
Denmark	1975–1979	0.45		0.34	0.76									
	1980–1984	0.48		0.30	0.62		0.00				0.03			
	1985–1989	0.50		0.35	0.70									
	1990–1994	0.53	0.35	0.41	0.78	1.18	0.00	0.00	0.01	0.31	0.02	0.03	0.09	0.83
Ecuador	1993–1994	0.03	0.02	0.04	1.48	2.00	0.00	0.02	0.09	0.54	0.00	0.00	0.00	0.00
Finland	1975–1979	0.60	0.02	0.07	0.12	4.11	0.00				0.04			
	1980–1984	0.68	0.08	0.15	0.23	1.93	0.00				0.07			
	1985–1989	0.75	0.11	0.17	0.23	1.62								
	1990–1994	677	0.13	0.15	0.22	1.15	0.00	0.00	0.00	0.09	0.00	0.00	0.06	0.76
France	1975–1979	2.76		3.25	1.18		0.00							
	1980–1984	3.37	0.62	1.61	0.48	2.60	0.00							
	1985–1989	3.21	0.54	1.03	0.32	1.92	0.00							
	1990–1994													
Germany [l]	1980–1984	0.81	0.20	0.54	0.67	2.68								
	1985–1989	0.83	0.15	0.43	0.51	2.84					0.02			
Greece	1990–1994	0.41	0.13	0.31	0.75	2.27	0.00	0.01	0.03	0.15	0.26	0.31	0.53	0.88
Hungary	1975–1979	0.36	0.03	0.05	0.14	1.66	0.00	0.09						
	1980–1984	0.54	0.09	0.18	0.33	1.93	0.00	0.14						
	1985–1989	0.72	0.14	0.22	0.31	1.62	0.00	0.01			0.01			
	1990–1994	0.76	0.15	0.20	0.27	1.40	0.00	0.00	0.01	0.08	0.02	0.05	0.20	0.78
Iceland	1990–1994	0.01	0.01	0.01	1.30	2.33	0.00	0.00	0.00	0.47	0.00	0.00	0.00	0.88
India	1975–1979	0.41	0.12	0.22	0.54	1.82	0.00				0.21			
	1980–1984	0.49	0.22	0.39	0.80	1.82	0.00				0.10			
	1985–1989	0.61	0.30	0.52	0.85	1.75	0.01				0.12			
	1990–1994	0.84	0.40	0.54	0.65	1.36	0.00	0.01	0.03	0.15	0.06	0.16	0.40	0.82
Indonesia	1980–1984	0.01	0.01	0.01	1.23	1.23								
	1985–1989	0.1	0.01	0.02	1.20	1.20								
Ireland	1985–1989		0.02	0.01		0.50								
	1991–1994	0.18	0.02	0.01	0.06	0.45	0.00	0.00	0.00	0.02	0.00	0.00	0.31	0.76
Jordan	1990–1994	0.47	0.42	0.57	1.23	1.36	0.01	0.02	0.05	0.19	0.20	0.32	0.45	0.72
Kuwait	1992–1994	0.06	0.02	0.02	0.37	0.97	0.00	0.00	0.00	0.11	0.00	0.00	0.00	0.57

Table 13 (continued)

Country / area	*Period*	*Monitored workers* (thousands)	*Measurably exposed workers* (thousands)	*Annual collective effective dose* (man Sv)	*Average annual effective dose (mSv)*		*Distribution ratio* [b] *(number of workers)*				*Distribution ratio (collective dose)*			
					Monitored workers	*Measurably exposed workers*	NR_{15}	NR_{10}	NR_5	NR_1	SR_{15}	SR_{10}	SR_5	SR_1
Mexico [u]	1985–1989 1990–1994	0.42 0.60	0.26	1.21 0.73	2.88 1.21	4.63	0.03				0.33			
Myanmar	1990–1994	0.02	0.02	0.02	1.26	1.26	0.03	0.03	0.09	0.50				
Netherlands	1990–1994	0.57	0.35	0.26	0.45	0.73	0.00	0.00	0.01	0.13	0.03	0.06	0.14	0.57
Norway	1990–1992	0.24	0.10	0.14	0.59	1.47	0.00	0.00	0.02	0.19				
Pakistan	1990–1994	0.23	0.22	2.07	8.90	12.6	0.26	0.38	0.55	0.81	0.72	0.82	0.94	1.00
Peru	1980–1984 1985–1989 1994	0.12 0.13 0.03	0.03	0.43 0.35 0.15	3.73 2.75 5.00	5.00	0.00	0.00	0.30	0.80				
Slovakia	1990–1994	0.30	0.21	0.27	0.93	1.30	0.00	0.00	0.01	0.36	0.04	0.04	0.09	0.78
Slovenia	1993–1994	0.34	0.34	0.17	0.49	0.49	0.00	0.00	0.00	0.08	0.00	0.00	0.02	0.28
Spain	1985–1989	0.92	0.83	1.61	1.74	1.93	0.01				0.11			
Sri Lanka	1990–1994	0.03	0.01	0.00	0.19	0.48	0.00	0.00	0.00	0.03	0.00	0.00	0.00	0.37
Syrian Arab Republic	1990–1994	0.06	0.01	0.03	0.48	3.16	0.00	0.00	0.01	.004	0.00	0.00	0.15	0.31
Thailand	1990–1994	0.22	0.08	0.23	1.04	2.89	0.01	0.01	0.04	0.17	0.44	0.48	0.69	0.92
United Kingdom [n]	1991	1.40		0.30	0.22									
Total reported data [o p]	1975–1979 1980–1984 1985–1989 1990–1994	5.66 7.91 15.9 13.5	7.63	5.21 5.72 16.6 12.8	0.92 0.72 1.04 0.95	1.68	0.00 0.00 0.01 0.01	0.02	0.04	0.24	0.11 0.05 0.17 0.24	0.29	0.42	0.81
World [q]	1975–1979 1980–1984 1985–1989 1990–1994	61 81 90 115 (100)	65 (60)	62 85 85 90 (86)	1.01 1.04 0.95 0.79 (0.86)	1.41 (1.40)	0.00 0.00 0.00 0.00 (0.00)	0.01 (0.01)	0.02 (0.03)	0.21 (0.21)	0.09 0.03 0.10 0.10 (0.15)	0.15 (0.20)	0.27 (0.31)	0.74 (0.74)
Radiotherapy														
Argentina	1985–1989 1990–1994	0.27 0.40	0.08 0.10	0.28 0.25	1.04 0.64	3.61 2.61	0.00 0.01	0.01	0.02	0.10	0.10 0.30	0.43	0.51	0.89

Table 13 (continued)

Country / area	*Period*	*Monitored workers* (thousands)	*Measurably exposed workers* (thousands)	*Annual collective effective dose* (man Sv)	*Average annual effective dose (mSv)*		*Distribution ratio [b] (number of workers)*				*Distribution ratio (collective dose)*			
					Monitored workers	*Measurably exposed workers*	NR_{15}	NR_{10}	NR_5	NR_1	SR_{15}	SR_{10}	SR_5	SR_1
Australia [c d]	1975–1979	0.64		1.47	2.30									
	1985–1989	0.78	0.63	0.27	0.34	0.42	0.00				0.17			
	1990–1994	1.08	0.71	0.25	0.23	0.35	0.00	0.00	0.00	0.03	0.17	0.21	0.26	0.46
Brazil [e]	1985–1989	0.72	0.24	0.90	1.24	3.73	0.02				0.44			
	1990–1994	0.80	0.30	1.17	1.47	3.95	0.01	0.02	0.05	0.17	0.57	0.64	0.76	0.94
Bulgaria	1990–1994	0.33		0.48	1.44									
Canada	1975–1979	0.54	0.35	0.75	1.40	2.14	0.01				0.27			
	1980–1984	0.62	0.36	0.63	1.01	1.78	0.00				0.08			
	1985–1989	0.72	0.43	0.59	0.82	1.38	0.00				0.05			
	1990–1994	1.03	0.44	0.35	0.34	0.80	0.00	0.00	0.01	0.09	0.07	0.09	0.17	0.61
China	1985–1989	2.54	0.35	3.54	1.39	10.0	0.02				0.31			
	1990–1994	1.46	1.40	1.68	1.15	1.20	0.01	0.01	0.03	0.39	0.12	0.17	0.28	0.67
China, Taiwan Province	1985–1989	0.36		0.06	0.16									
	1990–1994	0.42	0.14	0.05	0.13	0.36	0.00	0.00	0.00	0.01	0.09	0.09	0.14	0.29
Croatia	1990–1994	0.03	0.03	0.02	0.70	0.90								
Cuba	1990–1994	0.18	0.18	0.39	2.18	2.19	0.01	0.02	0.06	0.68	.0.14	0.20	0.32	0.92
Cyprus	1990–1994	0.01	0.01	0.01	0.85	0.96	0.00	0.00	0.00	0.36	0.00	0.00	0.00	0.67
Czech Republic [e g]	1975–1979	0.76	0.38	1.43	1.89	3.82	0.00				0.05			
	1980–1989	1.11	0.69	2.08	1.87	3.01	0.01				0.08			
	1985–1989	1.29	0.63	1.83	1.42	2.90	0.00				0.10			
	1990–1994	0.94	0.81	1.04	1.10	1.28	0.00	0.00	0.01	0.35	0.01	0.03	0.06	0.61
Denmark	1975–1979	0.92		1.95	2.12		0.03				0.37			
	1980–1984	1.01		1.12	1.11		0.01				0.17			
	1985–1989	1.01		0.38	0.38		0.00				0.02			
	1990–1994	1.03	0.24	0.15	0.15	0.64	0.00	0.00	0.00	0.04	0.00	0.03	0.14	0.62
Ecuador	1993–1994	0.06	0.05	0.07	1.06	1.44	0.01	0.02	0.04	0.35				
Finland	1980–1984	0.25	0.03	0.05	0.22	2.08	0.00				0.30			
	1985–1989	0.24	0.02	0.03	0.10	1.44	0.00				0.25			
	1990–1994	0.28	0.02	0.01	0.05	0.65	0.00	0.00	0.00	0.01	0.00	0.00	0.10	0.43

Table 13 (continued)

Country / area	*Period*	*Monitored workers* (thousands)	*Measurably exposed workers* (thousands)	*Annual collective effective dose* (man Sv)	*Average annual effective dose (mSv)*		*Distribution ratio* [b] *(number of workers)*				*Distribution ratio (collective dose)*			
					Monitored workers	*Measurably exposed workers*	NR_{15}	NR_{10}	NR_5	NR_1	SR_{15}	SR_{10}	SR_5	SR_1
France [m]	1975–1979 1980–1984 1985–1989 1990–1994	4.77 6.01 6.49	1.30 1.23	8.77 6.08 3.97	1.84 1.01 0.61	4.68 3.22	0.01 0.01 0.01							
Germany [l]	1980–1984 1985–1989	1.20 1.03	0.31 0.17	1.09 0.68	0.91 0.66	3.57 4.00					0.24 0.23			
Greece	1990–1994	0.22	0.01	0.03	0.11	2.00	0.00	0.00	0.01	0.03	0.00	0.19	0.51	0.88
Hungary	1975–1979 1980–1984 1985–1989 1990–1994	0.36 0.45 0.55 0.47	0.14 0.14 0.15 0.10	0.73 0.61 0.61 0.33	2.05 1.36 1.10 0.70	5.15 4.31 3.97 3.28	0.03 0.02 0.01 0.01	0.02	0.04	0.14	0.36 0.24 0.23 0.28	0.36	0.59	0.94
Iceland	1990–1994	0.04	0.01	0.01	0.18	0.60	0.00	0.00	0.00	0.02	0.00	0.00	0.00	0.83
India	1975–1979 1980–1984 1985–1989 1990–1994	2.49 2.98 4.17 4.52	1.43 1.53 2.28 2.35	3.91 3.39 3.94 3.15	1.57 1.14 0.95 0.70	2.73 2.22 1.73 1.34	0.02 0.01 0.01 0.00	0.01	0.03	0.15	0.39 0.30 0.23 0.17	0.26	0.43	0.81
Indonesia	1975–1979 1980–1984 1985–1989	0.09 0.31 0.23	0.09 0.30 0.22	0.19 0.50 0.35	2.10 1.60 1.55	2.20 1.68 1.63	0.00 0.00				0.02 0.04			
Ireland	1985–1989 1991–1994	0.30 0.28	0.14 0.07	0.15 0.03	0.50 0.12	1.05 0.43	0.00	0.00	0.00	0.03	0.00	0.00	0.04	0.58
Jordan	1990–1994	0.02	0.02	0.02	1.03	1.03	0.00	0.00	0.00	0.44	0.00	0.00	0.00	0.57
Kuwait	1992–1994	0.06	0.00	0.01	0.17	1.35	0.00	0.00	0.00	0.03	0.00	0.00	0.00	0.33
Mexico [u]	1985–1989 1990–1994	0.31 0.66	0.26	0.88 0.45	2.84 0.68	3.41	0.03				0.33			
Myanmar	1990–1994	0.02	0.02	0.01	0.58	0.58	0.00	0.00	0.00	0.14				
Netherlands	1990–1994	1.55	0.49	0.38	0.25	0.77	0.00	0.00	0.00	0.02	0.49	0.52	0.56	0.76
Pakistan	1990–1994	0.13	0.12	1.35	10.5	11.6	0.32	0.45	0.64	0.86	0.68	0.82	0.94	1.00
Peru	1980–1984 1985–1989 1994	0.09 0.09 0.05	0.05	0.54 0.48 0.24	6.18 5.17 5.00	5.00	0.00	0.08	0.42	0.88				

Table 13 (continued)

Country / area	*Period*	*Monitored workers* (thousands)	*Measurably exposed workers* (thousands)	*Annual collective effective dose* (man Sv)	*Average annual effective dose (mSv)*		*Distribution ratio [b] (number of workers)*				*Distribution ratio (collective dose)*			
					Monitored workers	*Measurably exposed workers*	NR_{15}	NR_{10}	NR_5	NR_1	SR_{15}	SR_{10}	SR_5	SR_1
Slovak Republic	1990–1994	0.30	0.17	0.26	0.88	1.50	0.00	0.01	0.02	0.23	0.03	0.11	0.21	0.75
Slovenia	1993–1994	0.07	0.50	0.01	0.08	0.13	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Spain	1985–1989	1.01	0.96	0.88	0.86	0.91	0.00				0.02			
Sri Lanka	1990–1994	0.10	0.04	0.06	0.63	1.56	0.01	0.01	0.02	0.06	0.37	0.45	0.52	0.64
Syrian Arab Republic	1990–1994	0.04	0.01	0.01	0.29	1.37	0.00	0.00	0.00	0.04	0.00	0.00	0.12	0.48
Thailand	1990–1994	0.55	0.04	0.04	0.08	1.05	0.00	0.00	0.00	0.01	0.26	0.32	0.47	0.76
United Kingdom [n]	1991	2.68		0.40	0.15									
United Rep. of Tanzania	1990–1994	0.02	0.02	0.24	10.43	10.43	0.06	0.39	0.79	1.00	0.10	0.57	0.91	1.00
Total reported data [o p]	1975–1979	9.31		16.5	1.78		0.12				0.30			
	1980–1984	13.3		15.3	1.15		0.01				0.20			
	1985–1989	18.8		16.6	0.88		0.01				0.21			
	1990–1994	19.8	9.41	13.0	0.65	1.38	0.00	0.01	0.03	0.15	0.25	0.34	0.46	0.79
World [q]	1975–1979	84		190	2.23									
	1980–1984	110		180	1.58									
	1985–1989	110		100	0.87									
	1990–1994	120	48	65	0.55	1.33	0.00	0.01	0.02	0.13	0.15	0.25	0.37	0.74
		(105)	(52)	(72)	(0.68)	(1.39)	(0.00)	(0.01)	(0.02)	(0.16)	(0.17)	(0.27)	(0.39)	(0.76)
All other medical uses [v]														
Australia	1991–1994	0.05	0.01	0.00	0.06	0.58	0.00	0.00	0.00	0.02	0.00	0.00	0.00	0.70
Brazil [e]	1990–1994	0.16	0.01	0.02	0.11	1.68	0.00	0.00	0.01	0.02	0.00	0.28	0.49	0.85
Bulgaria	1990–1994	0.25	0.02	0.06	0.26		0.00	0.00	0.00	0.02				
Canada	1990–1994	21.3	2.66	1.75	0.08	0.66	0.00	0.00	0.00	0.02	0.08	0.12	0.22	0.57
Czech Republic [g]	1975–1979	6.78	1.89	5.16	0.76	2.73	0.00				0.13			
	1980–1984	9.38	3.62	7.80	0.83	2.15	0.00				0.08			
	1985–1989	11.6	4.04	9.12	0.78	2.25	0.00				0.10			
Cuba	1991–1994	0.11	0.11	0.14	1.20	1.21	0.00	0.00	0.02	0.59	0.00	0.02	0.10	0.81
Cyprus	1990–1994	0.09	0.04	0.03	0.29	0.75	0.00	0.00	0.00	0.11	0.00	0.00	0.05	0.66
Ecuador	1993–1994	0.03	0.03	0.04	1.10	1.10	0.00	0.00	0.00	0.49				
Germany [w]	1990–1994	223	25.0	23.7	0.11	0.94	0.00	0.00	0.00	0.02	0.09	0.12	0.22	0.67
Greece	1990–1994	0.08	0.01	0.03	0.34	2.20	0.00	0.01	0.02	0.09	0.13	0.22	0.40	0.90
Hungary	1990–1994	0.38	0.02	0.02	0.04	0.95	0.00	0.00	0.00	0.01	0.00	0.00	0.06	0.64
Iceland	1990–1994	0.06	0.00	0.00	0.01	0.26	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Table 13 (continued)

Country / area	*Period*	*Monitored workers* (thousands)	*Measurably exposed workers* (thousands)	*Annual collective effective dose* (man Sv)	*Average annual effective dose (mSv)*		*Distribution ratio* [b] *(number of workers)*				*Distribution ratio (collective dose)*			
					Monitored workers	*Measurably exposed workers*	NR_{15}	NR_{10}	NR_5	NR_1	SR_{15}	SR_{10}	SR_5	SR_1
Japan	1990–1994	173	45.2	66.1	0.38	1.46	0.00	0.01	0.02	0.08	0.17	0.25	0.41	0.80
Kuwait	1992–1994	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Myanmar	1990–1994	0.04	0.04	0.03	0.75	0.75	0.01	0.01	0.01	0.14				
Netherlands	1990–1993	4.30	0.62	0.41	0.10	0.63	0.00	0.00	0.00	0.02	0.31	0.36	0.39	0.66
Norway	1990–1992	1.51	0.43	0.47	0.31	1.09	0.00	0.00	0.01	0.06				
Pakistan	1990–1994	0.50	0.47	2.38	4.78	5.11	0.09	0.15	0.22	0.39	0.61	0.77	0.87	0.95
Slovakia [g]	1990–1994	0.53	0.09	0.08	0.15	2.01	0.00	0.00	0.01	0.07	0.28	0.34	0.50	0.83
Sri Lanka	1991–1994	0.01	0.01	0.09	9.76	12.1	0.19	0.28	0.28	0.39	0.86	0.96	0.96	0.98
Sweden [x]	1990–1994	7.50		2.38	0.32									
Switzerland	1990–1994	27.7		1.25	0.05		0.00	0.00	0.00	0.01	0.01	0.04	0.16	0.52
Total reported [o p]	1990–1994	461	76.0	98.9	0.21	1.30	0.00	0.00	0.01	0.04	0.15	0.22	0.36	0.74

a Data are annual averages over the periods indicated.
b The values of NR are for the monitored workforce.
c For 1975–1979 the number of workers and the collective dose have been scaled up by a factor of 1.43, since the reported data included only about 70% of the exposed workforce in Australia.
d The method of dose recording was different in the two periods for which data are reported, and this may account partly for the differences in data. Average individual doses for 1975–1979 were calculated from the total of the reported doses for an occupational category divided by the estimated number of workers in that category, with the results rounded to the nearest 1 mSv. In 1990 the estimates were based directly on the results of individual monitoring; in the absence of data for 1985–1989, the data for 1990 have been assumed to be representative of that period.
e Reported data have been rationed up from a sample of approximately 25% of monitored workers.
f The data includes exposures from dental radiography and other medical uses.
g The data for 1975–1989 refer to Czechoslovakia. Scaling down to 60% would give equivalent data for the Czech Republic.
h Where lead aprons are worn the dosemeters are worn below the aprons.
i Reported data contain a contribution from dental radiography.
j Reported data contain a contribution from nuclear medicine.
k The number of workers and the collective dose have been scaled up by a factor of 1.33, since the reported data covered only 75% of those monitored.
l 1980–1989 data from the German Democratic Republic.
m Reported data contain a contribution from radiotherapy.
n Reported data have been rationed up from a sample of approximately 33% of monitored workers.
o The total for measurably exposed workers has been rationed up to take account of countries that did not report the number of measurably exposed workers, but did report a figure for monitored workers.
p These data should be interpreted with care, particularly because the countries included in the summations for the respective five-year periods may not be the same, depending on whether data were reported for the period in question. Consequently, direct comparison between data for different periods is invalid to the extent that the data comprise contributions from different countries. It should also be noted that the data on NR_{15} and SR_{15} are averages of data reported on these ratios. In general, these data are less complete than those that form the basis of the summated number of workers and collective doses.
q The values shown in parentheses are the world estimates based on the standard method given in Section I.E; however, the Committee identified a more robust method of estimation for this instance, based on the regional value for the United States being taken to be equivalent to the rest of OECD. These are the values shown without parentheses.
r Within the data from 1990–1994, the data concerning 1990 only relate to the Federal Republic of Germany.
s Data for dentists in private practice only.
t The data are specifically for the years 1975, 1980 and 1985; they are assumed here to be representative, respectively of 1975–1979, 1980–1984 and 1985–1989.
u In the absence of data for 1985–1989, the data for 1990 have been assumed representative.
v No world estimate has been made because of the undefined nature of the sectors covered.
w The data for 1980–1989 is a combination of data previously reported for the German Democratic Republic and the Federal Republic of Germany.
x These values apply to all medical uses of radiation since no division into different categories could be done.

Table 14
Exposures to workers from all medical uses of radiation [a]
Data from UNSCEAR Survey of Occupational Exposures

Country / area	Period	Monitored workers (thousands)	Measurably exposed workers (thousands)	Annual collective effective dose (man Sv)	Average annual effective dose (mSv)		Distribution ratio [b] (number of workers)				Distribution ratio (collective dose)			
					Monitored worker	Measurably exposed workers	NR_{15}	NR_{10}	NR_5	NR_1	SR_{15}	SR_{10}	SR_5	SR_1
Argentina	1985–1989 1990–1994	3.45 6.81	1.20	3.74 10.39	1.08 1.53	3.12 3.99	0.13 0.04	0.04	0.05	0.18	0.48 0.60	0.62	0.68	0.93
Australia [c d]	1975–1979 1985–1989 1990–1994	6.23 15.80 14.77	8.96	3.45 1.11 2.01	0.55 0.07 0.14	0.12 0.23	0.00 0.00	0.00	0.00	0.02	0.04 0.14	0.15	0.21	0.54
Brazil [e]	1985–1989 1990–1994	76.00 6.39	23.00	115.00 3.37	1.51 0.53	4.96 3.32	0.00	0.01	0.02	0.07	0.43	0.54	0.70	0.93
Bulgaria	1990–1994	3.92	0.33	1.75	0.45	4.66	0.00	0.00	0.00	0.04	0.01	0.02	0.05	0.23
Canada	1975–1979 1980–1984 1985–1989 1990–1994	39.6 51.7 62.90 63.65	11.8 7.88 10.80 6.82	10.4 8.30 9.18 5.65	0.26 0.16 0.15 0.09	0.88 1.05 0.85 0.83	0.00 0.00 0.00 0.00	0.00	0.00	0.02	0.08 0.04 0.06 0.07	0.09	0.21	0.67
China	1985–1989 1990–1994	86.80 13.96	14.40	156.00 22.90	1.80 1.64	10.90 1.76	0.03 0.01	0.03	0.05	0.32	0.43 0.24	0.33	0.43	0.77
China, Taiwan Province	1980–1984 1985–1989 1990–1994	3.08 3.98 6.01	1.35	1.77 1.96 0.93	0.57 0.49 0.15	0.69	0.00	0.00	0.00	0.01	0.02	0.02	0.08	0.16
Croatia	1990–1994	3.44	1.89	0.62	0.18	0.33								
Cuba	1990–1994	0.46	0.46	0.99	2.18	2.17	0.01	0.05	0.13	0.71	0.11	0.18	0.31	0.92
Cyprus	1990–1994	0.29	0.17	0.21	0.72	1.26	0.01	0.01	0.02	0.21	0.17	0.21	0.30	0.86
Czech Republic [f]	1975–1979 1980–1984 1985–1989 1990–1994	6.78 9.38 11.60 9.40	1.89 3.62 4.04	5.16 7.80 9.12 7.82	0.76 0.83 0.78 0.83	2.73 2.15 2.25 1.51	0.00 0.00 0.00 0.00	0.00	0.01	0.19	0.13 0.08 0.10 0.05	0.09	0.16	0.69
Denmark	1975–1979 1980–1984 1985–1989 1990–1994	6.13 6.02 6.04 5.28	1.76	3.32 2.08 1.18 1.04	0.54 0.35 0.20 0.20	0.59	0.00 0.00 0.00 0.00	0.00	0.00	0.05	0.22 0.10 0.01 0.01	0.02	0.09	0.60
Ecuador	1990–1994	0.85	0.56	0.70	0.82	1.25	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Table 14 (continued)

Country / area	*Period*	*Monitored workers* (thousands)	*Measurably exposed workers* (thousands)	*Annual collective effective dose* (man Sv)	*Average annual effective dose (mSv)*		*Distribution ratio* [b] *(number of workers)*				*Distribution ratio (collective dose)*			
					Monitored worker	*Measurably exposed workers*	NR_{15}	NR_{10}	NR_5	NR_1	SR_{15}	SR_{10}	SR_5	SR_1
Finland [g]	1975–1979	4.98	0.18	1.17	0.23	6.55	0.00				0.45			
	1980–1984	5.60	0.58	1.23	0.21	2.10	0.00				0.12			
	1985–1989	6.18	0.49	1.22	0.20	2.50	0.00				0.21			
	1990–1994	5.85		1.30	0.22	2.25	0.00	0.00	0.01	0.05	0.24	0.35	0.52	0.89
France	1975–1979	40.9		49.3	1.21		0.00							
	1980–1984	59.2	8.06	36.0	0.61	4.46	0.00							
	1985–1989	73.7	0.42	25.1	0.34	3.06	0.00							
Gabon	1990–1994	0.01	0.00	0.00	0.20		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Germany [h]	1980–1984	158.6	22.2	29.54	0.34	1.18	0.00				0.14			
	1985–1989	209.6	23.19	26.06	0.12	1.12	0.00				0.16			
	1990–1994	230.15		23.86	0.10	0.95	0.00	0.00	0.00	0.02	0.09	0.12	0.22	0.67
Greece	1990–1994	4.81	1.13	4.12	0.86	3.65	0.01	0.02	0.04	0.13	0.42	0.53	0.70	0.93
Hungary	1975–1979	7.80	1.43	3.19	0.41	2.23	0.00				0.16			
	1980–1984	9.15	1.26	2.41	0.26	1.91	0.00				0.13			
	1985–1989	9.07	1.29	2.34	0.26	1.82	0.00				0.11			
	1990–1994	8.38		1.26	0.15	1.38	0.00	0.00	0.00	0.04	0.10	0.14	0.28	0.76
Iceland	1990–1994	0.59	0.14	0.14	0.24	1.01	0.00	0.00	0.01	0.05	0.11	0.22	0.30	0.71
India	1975–1979	9.58	5.22	7.89	0.82	1.51	0.00				0.30			
	1980–1984	11.6	5.74	6.56	0.57	1.14	0.00				0.22			
	1985–1989	15.20	8.03	8.02	0.53	1.00	0.00				0.17			
	1990–1994	16.76		6.38	0.38	0.74	0.00	0.00	0.02	0.08	0.14	0.22	0.37	0.75
Indonesia	1975–1979	1.07	1.02	1.78	1.67	1.75	0.00				0.02			
	1980–1984	2.16	2.06	3.44	1.60	1.68	0.00				0.01			
	1985–1989	2.53	2.41	4.24	1.68	1.77	0.00				0.01			
Ireland	1985–1989	1.69	0.28	0.22	0.13	0.78	0.00				0.00			
	1991–1994	2.86	0.24	0.14	0.05	0.58	0.00	0.00	0.00	0.02	0.00	0.02	0.13	0.52
Italy	1985–1989	44.60	12.60	21.00	0.47	1.66	0.00				0.27			
Japan	1975–1979	55.3	21.7	35.7	0.65	1.65								
	1980–1984	111	34.2	44.0	0.40	1.29								
	1985–1989	142.00	38.60	46.60	0.33	1.21								
	1990–1994	178.4	45.67	66.63	0.37	1.46	0.00	0.01	0.02	0.08	0.17	0.25	0.41	0.80
Jordan	1990–1994	0.49	0.44	0.59	1.21	1.33	0.01	0.02	0.05	0.20	0.19	0.31	0.43	0.71

Table 14 (continued)

Country / area	*Period*	*Monitored workers* (thousands)	*Measurably exposed workers* (thousands)	*Annual collective effective dose* (man Sv)	*Average annual effective dose (mSv)*		*Distribution ratio* [b] *(number of workers)*				*Distribution ratio (collective dose)*			
					Monitored worker	*Measurably exposed workers*	NR_{15}	NR_{10}	NR_{5}	NR_{1}	SR_{15}	SR_{10}	SR_{5}	SR_{1}
Kuwait	1990–1994	0.62	0.11	0.20	0.33	1.89	0.00	0.00	0.01	0.06	0.15	0.18	0.25	0.58
Mexico	1985–1989 1990–1994	0.73 1.27	0.52	2.09 1.18	2.86 0.93	4.02	0.03				0.24			
Myanmar	1990–1994	0.10	0.10	0.08	0.78	0.78	0.01	0.01	0.02	0.18	0.00	0.00	0.00	0.00
Netherlands	1990–1994	19.56	6.11	8.19	0.42	1.34	0.01	0.01	0.02	0.06	0.33	0.45	0.60	0.84
Norway	1990–1994	4.74	1.52	2.90	0.61	1.91	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Pakistan	1990–1994	1.50	1.43	8.10	5.39	5.66	0.13	0.19	0.28	0.50	0.65	0.77	0.88	0.97
Peru	1980–1984 1985–1989 1990–1994	1.58 1.70 1.98	1.67	7.03 7.14 5.34	4.46 4.20 2.70	3.19	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Portugal	1985–1989	3.83	0.97	2.01	0.52	2.06	0.00							
Slovakia	1990–1994	4.52	0.99	1.58	0.35	1.59	0.00	0.00	0.01	0.10	0.11	0.16	0.30	0.80
Slovenia	1990–1994	2.22	1.76	0.84	0.38	0.48	0.00	0.00	0.00	0.06	0.01	0.01	0.06	0.30
South Africa	1975–1979 1980–1984 1985–1989	8.76 10.7 12.1	5.49 4.13 2.64	0.57 7.37 9.53	0.06 0.69 0.79	0.10 1.79 3.61	0.00 0.01 0.00				0.08 0.52 0.23			
Spain	1985–1989	37.70	34.00	29.30	0.78	0.86	0.00				0.12			
Sri Lanka	1990–1994	0.37	0.13	0.27	0.73	2.08	0.01	0.01	0.02	0.07	0.46	0.52	0.58	0.77
Sweden	1975–1979 1980–1984 1985–1989 1990–1994	11.5 12.8 13.20 7.79	1.29 1.38 3.66	2.84 2.53 3.13 2.39	0.25 0.20 0.24 0.31	2.21 1.83 0.86	0.01 0.00 0.00							
Switzerland	1975–1979 1980–1984 1985–1989 1990–1994	21.5 30.1 36.10 38.68		6.20 4.97 1.83 1.50	0.29 0.17 0.05 0.04		0.00 0.00 0.00 0.00	0.00	0.00	0.01	0.12 0.09 0.03 0.04	0.06	0.17	0.50
Syrian Arab Republic	1990–1994	0.90	0.08	2.61	2.90	32.63	0.00	0.00	0.00	0.01	0.00	0.00	0.02	0.13

Table 14 (continued)

Country / area	*Period*	*Monitored workers* (thousands)	*Measurably exposed workers* (thousands)	*Annual collective effective dose* (man Sv)	*Average annual effective dose (mSv)*		*Distribution ratio [b] (number of workers)*				*Distribution ratio (collective dose)*			
					Monitored worker	*Measurably exposed workers*	NR_{15}	NR_{10}	NR_5	NR_1	SR_{15}	SR_{10}	SR_5	SR_1
Thailand	1990–1994	4.83	1.45	1.03	0.21	0.71	0.00	0.00	0.01	0.04	0.20	0.28	0.43	0.77
United Kingdom [i]	1980–1984	39		28	0.71									
	1985–1989	40.00		8.40	0.21									
	1990–1994	37.81	0.00	4.10	0.11									
United States [j]	1975–1979	485		460	0.95									
	1980–1984	584		410	0.70									
	1985–1989	734	267	280	0.38	1.05								
United Rep. Tanzania	1990–1994	0.44	0.43	2.14	4.91	4.98	0.02	0.16	0.51	0.86	0.06	0.42	0.82	0.98
Reported Total [k l]	1975–1979	671		577	0.86		0.03				0.16			
	1980–1984	1060		588	0.55		0.00				0.11			
	1985–1989	1520		644	0.42		0.01				0.34			
	1990–1994	710	160.00	205	0.29	1.30	0.00	0.00	0.01	0.05	0.21	0.28	0.41	0.77
World estimate [k m]	1975–1979	1280	650	993	0.78	1.50	0.00				0.14			
	1980–1984	1890	520	1140	0.60	1.70	0.00				0.10			
	1989–1989	2220	590	1030	0.47	1.70	0.01				0.24			
	1990–1994	2320	550	760	0.33	1.39	0.00	0.00	0.01	0.06	0.14	0.22	0.35	0.71
		(1850)	(475)	(695)	(0.38)	(1.47)	(0.00)	(0.00)	(0.01)	(0.07)	(0.15)	(0.22)	(0.35)	(0.70)

a Data are annual averages over the periods indicated.

b The values of NR are for the monitored workforce.

c The number of workers and the collective dose have been scaled up by a factor of 1.43, since the reported data included only about 70% of the exposed workforce in Australia.

d The method of dose recording was different in the two periods for which data are reported, and this may account partly for the differences in data. Average individual doses for 1975–1979 were calculated from the total of the reported doses for an occupational category divided by the estimated number of workers in that category, with the results rounded to the nearest 0.1 mSv. In 1990 the estimates were based directly on the results of individual monitoring in the absence of data for 1985–1989, the data for 1990 have been assumed to be representative of that period.

e Reported data have been rationed up from a sample of approximately 25% of monitored workers.

f The data for 1985–1989 refer to Czechoslovakia.

g Reported doses are overestimates because the dosimeter is calibrated in terms of the skin surface dose and is worn above aprons where these are used. For x-ray diagnostic radiology, preliminary studies indicate that the overestimate may be by a factor in the range of 3-30; about 60% of the occupational exposures reported for all medical uses of radiation are currently reported to arise in diagnostic radiology.

h Within the data from 1990–1994, the data concerning 1990 only relate to the Federal Republic of Germany.

i Reported data have been rationed up from a sample of approximately 33% of monitored workers.

j Data for [E1, E2 and E3]. The data are specifically for the years 1975, 1980 and 1985; they are assumed here to be representative, respectively, of 1975–1979, 1980–1984 and 1985–1989.

k The figures quoted are rounded values.

l The total for measurably exposed workers has been rationed up to take account of countries that did not report the number of measurably exposed workers, but did report a figure for monitored workers. Reported data contain a contribution from radiotherapy.

m These data should be interpreted with care, particularly because the countries included in the summations for the respective five-year periods may not be the same, depending on whether the data were reported for the period in question. Consequently, direct comparison between data for different periods is invalid to the extent that the data comprise contributions from different countries. It should also be noted that the data on NR_{15} and SR_{15} are averages of data reported on these ratios. In general, these data are less complete than those that form the basis of the summated number of workers and collective doses.

Table 15
Regional exposures to workers from medical uses of radiation (1990–1994) [a]

Region	*Monitored workers*	*Measurably exposed workers* [b]	*Annual collective effective dose (man Sv)*	*Average annual effective dose (mSv)*		*Distribution ratio* [c] *(number of workers)*				*Distribution ratio (collective dose)*			
				Monitored workers	*Measurably exposed workers*	NR_{15}	NR_{10}	NR_5	NR_1	SR_{15}	SR_{10}	SR_5	SR_1
Diagnostic radiology													
East and South-East Asia	21 415	13 925	22.71	1.06	1.63	0.01	0.02	0.03	0.19	0.24	0.32	0.42	0.75
Eastern Europe	25 291	8 155	9.8	0.39	1.20	0.00	0.00	0.00	0.09	0.06	0.09	0.18	0.65
Indian subcontinent	11 551	6 282	5	0.43	0.80	0.00	0.00	0.02	0.07	0.34	0.41	0.53	0.80
Latin America	12 827	4 776	15.84	1.23	3.32	0.03	0.04	0.05	0.17	0.58	0.61	0.68	0.93
OECD except United States	62 162	20 763	18.66	0.30	0.90	0.00	0.01	0.01	0.06	0.31	0.41	0.56	0.81
Remainder	1 848	1 051	4.64	2.51	4.42	0.01	0.06	0.20	0.40	0.07	0.38	0.74	0.95
Total reported	135 094	54 857	76.7	0.57	1.40	0.01	0.01	0.02	0.10	0.27	0.35	0.46	0.75
Dental radiology													
East and South-East Asia	272	61	0.03	0.11	0.49	0.00	0.00	0.00	0.02	0.16	0.28	0.28	0.71
Eastern Europe	889	168	0.14	0.16	0.83	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.05
Indian subcontinent	730	316	0.11	0.15	0.35	0.00	0.00	0.00	0.03	0.03	0.05	0.15	0.55
Latin America	795	76	0.16	0.20	2.11	0.00	0.00	0.01	0.04	0.42	0.48	0.54	0.66
OECD except United States	78 715	4 671	3.52	0.04	0.75	0.00	0.00	0.00	0.00	0.30	0.36	0.43	0.67
Remainder	33	13	0.01	0.33	0.85	0.01	0.01	0.01	0.08	0.40	0.40	0.40	0.72
Total reported	81 434	5 305	3.97	0.05	0.75	0.00	0.00	0.00	0.00	0.28	0.33	0.40	0.64
Nuclear medicine													
East and South-East Asia	734	320	0.39	0.53	1.22	0.00	0.00	0.01	0.11	0.28	0.32	0.59	0.89
Eastern Europe	2 401	1 607	1.63	0.68	1.01	0.00	0.00	0.01	0.21	0.02	0.04	0.10	0.66
Indian subcontinent	1 099	634	2.61	2.37	4.12	0.06	0.09	0.14	0.29	0.58	0.68	0.83	0.96
Latin America	1 069	632	2.46	2.30	3.89	0.03	0.06	0.12	0.39	0.41	0.48	0.61	0.94
OECD except United States	7 615	3 982	4.91	0.64	1.23	0.00	0.00	0.02	0.24	0.03	0.05	0.18	0.81
Remainder	593	455	0.78	1.32	1.72	0.01	0.02	0.04	0.17	0.15	0.23	0.36	0.62
Total reported	13 511	7 630	12.80	0.95	1.68	0.01	0.02	0.04	0.24	0.24	0.29	0.42	0.81

Table 15 (continued)

Region	*Monitored workers*	*Measurably exposed workers* [b]	*Annual collective effective dose (man Sv)*	*Average annual effective dose (mSv)*		*Distribution ratio* [c] *(number of workers)*				*Distribution ratio (collective dose)*			
				Monitored workers	*Measurably exposed workers*	NR_{15}	NR_{10}	NR_5	NR_1	SR_{15}	SR_{10}	SR_5	SR_1
Radiotherapy													
East and South-East Asia	2 441	1 593	1.78	0.73	1.12	0.01	0.01	0.02	0.24	0.12	0.17	0.28	0.66
Eastern Europe	2 146	1 387	2.14	1.00	1.54	0.00	0.01	0.02	0.26	0.07	0.11	0.19	0.69
Indian subcontinent	4 747	2 515	4.56	0.96	1.81	0.01	0.02	0.05	0.17	0.32	0.43	0.58	0.86
Latin America	1 483	667	2.13	1.44	3.19	0.01	0.02	0.06	0.26	0.44	0.52	0.63	0.93
OECD except United States	8 863	3 187	2.06	0.23	0.65	0.00	0.00	0.00	0.04	0.21	0.24	0.31	0.63
Remainder	160	63	0.29	1.81	4.60	0.01	0.06	0.11	0.25	0.08	0.47	0.76	0.92
Total reported	19 840	9 412	13.0	0.65	1.38	0.00	0.01	0.03	0.15	0.25	0.34	0.46	0.79
All other medical uses													
East and South-East Asia	44	42	0.03	0.68	0.71	0.01	0.01	0.01	0.14				
Eastern Europe	1 154	127	0.16	0.14	1.26	0.00	0.00	0.00	0.04	0.22	0.27	0.41	0.79
Indian subcontinent	508	473	2.47	4.86	5.22	0.09	0.15	0.22	0.39	0.62	0.78	0.87	0.95
Latin America	311	157	0.2	0.64	1.27	0.00	0.00	0.01	0.28	0.00	0.05	0.15	0.82
OECD except United States	458 849	75 199	96	0.21	1.28	0.00	0.00	0.01	0.04	0.15	0.21	0.35	0.76
Remainder	104	36	0.03	0.29	0.83	0.00	0.00	0.00	0.10	0.00	0.00	0.05	0.66
Total reported	460 970	76 034	98.89	0.21	1.30	0.00	0.00	0.01	0.04	0.15	0.22	0.36	0.74
All medical uses													
East and South-East Asia	24 904	15 943	24.94	1.00	1.56	0.01	0.02	0.03	0.19	0.23	0.31	0.41	0.75
Eastern Europe	31 881	11 091	13.87	0.44	1.25	0.00	0.00	0.01	0.09	0.06	0.09	0.17	0.65
Indian subcontinent	18 635	10 220	14.75	0.79	1.44	0.01	0.02	0.04	0.11	0.42	0.52	0.65	0.87
Latin America	16 485	6 308	20.79	1.26	3.30	0.02	0.02	0.03	0.12	0.53	0.57	0.66	0.93
OECD except United States	613 345	112 847	124.58	0.20	1.10	0.00	0.00	0.01	0.04	0.17	0.23	0.38	0.76
Remainder	2 738	1 226	5.752	2.10	4.69	0.01	0.03	0.09	0.21	0.05	0.20	0.38	0.55
Reported Total	707 988	157 635	204.68	0.29	1.30	0.00	0.00	0.01	0.07	0.21	0.28	0.41	0.77

a Data are annual values averaged over the period reported.
b The values for measurably exposed workers has been rationed up to take account of countries that did not report the number of measurably exposed workers, but did report a figure for monitored workers.
c The values of NR are for monitored workers.

Table 16
Summary of worldwide exposures from medical uses of radiation [a]

Practice	*Monitored workers (thousands)*	*Measurably exposed workers (thousands)* [b]	*Annual average collective effective dose (man Sv)*	*Annual average individual dose (mSv)*	
				Monitored workers	*Measurably exposed workers*
1975–1979					
Diagnostic radiology	630		600	0.94	
Dental practice	370		120	0.32	
Nuclear medicine	61		62	1.01	
Radiotherapy	84		190	2.23	
All medicine	1 300		990	0.78	
1980–1984					
Diagnostic radiology	1 100		720	0.68	
Dental practice	500		93	0.19	
Nuclear medicine	81		85	1.04	
Radiotherapy	110		180	1.58	
All medicine	1 900		1 100	0.60	
1985–1989					
Diagnostic radiology	1 400		760	0.56	
Dental practice	480		25	0.05	
Nuclear medicine	90		85	0.95	
Radiotherapy	110		100	0.87	
All medicine	2 200		1 000	0.47	
1990–1994					
Diagnostic radiology [c]	950	350	470	0.50	1.34
	(840)	(330)	(485)	(0.57)	(1.47)
Dental practice [c]	265	17	16	0.06	0.89
	(240)	(17)	(13)	(0.04)	(0.77)
Nuclear medicine [c]	115	65	90	0.79	1.41
	(100)	(60)	(86)	(0.86)	(1.40)
Radiotherapy [c]	120	48	65	0.55	1.33
	(105)	(52)	(72)	(0.68)	(1.39)
Other uses	870	70	119	0.14	1.70
	(555)	(16)	(39)	(0.07)	(2.44)
All medicine [c]	2 320	550	760	0.33	1.39
	(1 840)	(475)	(695)	(0.38)	(1.47)

a The data are annual values averaged over the respective five year periods and are, in general, quoted to two significant figures.

b The total for measurably exposed workers has been rationed up to take account of countries that did not report the number of measurably exposed workers, but did report a figure for monitored workers.

c The values shown in brackets are the world estimates based on the standard method given in Section I.E; however the Committee identified a more robust method of estimation for this instance, based on the regional value for the United States being taken to be equivalent to the rest of OECD (see para 156).

Table 17
Worldwide exposure from all medical uses of radiation [a]

Region	*Monitored workers (thousands)*	*Measurably exposed workers (thousands)*	*Average annual collective dose (man Sv)*	*Average annual individual dose to monitored workers (mSv)*	*Average annual individual dose to measurably exposed workers (mSv)*	*Collective effective dose* [b] *per unit GDP (man Sv per 10^{12} US$)*
1975–1979						
East and South-East Asia	4		70	1.7		44
Eastern Europe [c]	190		110	0.57		94
Indian subcontinent	12		10	0.82		81
Latin America						
OECD except United States	360		220	0.61		74
United States (estimate) [d]	490		460	0.95		250
Remainder	230		190	0.84		160
Total	1 300		990	0.78		130
1980–1984						
East and South-East Asia	10		16	1.6		37
Eastern Europe [c]	460		150	0.31		64
Indian subcontinent	15		9	0.57		33
Latin America	60		270	4.5		350
OECD except United States	610		210	0.35		43
United States (estimate) [d]	580		410	0.70		120
Remainder	160		90	0.55		79
Total	1 900		1 100	0.60		87
1985–1989						
Asia	96		170	1.8		440
East and South-East Asia	17		29	1.7		56
Eastern Europe [c]	430		130	0.31		38
Indian subcontinent	19		10	0.53		30
Latin America	110		180	1.6		220
OECD except United States	740		190	0.27		24
United States (estimate) [d]	730		280	0.38		58
Remainder	75		35	0.47		56
Total	2 200		1 000	0.47		54
1990–1994						
East and South-East Asia	44	28	45	1.00	1.56	40
Eastern Europe	420	145	182	0.44	1.25	105
Indian subcontinent	26	14	21	0.79	1.44	41
Latin America	22	9	28	1.26	3.30	32
OECD except United States	870	160	180	0.20	1.10	16
United States [d]	870	160	180	0.20	1.10	16
	(400)	(90)	(115)			21
Remainder	61	27	127	2.10	4.69	94
World	2 320	550	760	0.33	1.39	34
	(1 850)	(475)	(695)	(0.38)	(1.47)	(31)

a The data are annual averages over the respective five year periods and are, in general, quoted to two significant figures.
b The normalized collective doses per unit GDP for the three five year periods are expressed, respectively, in terms of 1977, 1983, 1989 and 1994 prices; direct comparison between the values for different periods is possible only after correcting for these different price bases.
c Including the whole of the former USSR.
d The values shown in brackets are the world estimates based on the standard method given in Section I.E; however the Committee identified a more robust method of estimation for this instance, based on the regional value for the United States being taken to be equivalent to the rest of OECD (see para 156).

Table 18
Exposures to medical staff involved in diagnostic radiology in the United Kingdom in 1991
[H3]

Occupational group	*Number of workers in dose range*				*Total number of workers*	*Annual collective dose (man Sv)*	*Average annual dose (mSv)*
	0 –1 mSv	*1 –5 mSv*	*5 –15 mSv*	*>15 mSv*			
Radiographers	5 663	55	1	0	5 719	0.28	0.05
Radiologists	7 29	38	0	0	767	0.14	0.18
Cardiologists	1 71	22	2	1	196	0.089	0.44
Other clinicians	4 65	9	0	0	474	0.044	0.09
Nurses	1 522	38	1	0	1 561	0.13	0.08
Technicians	1 070	27	1	0	1 098	0.090	0.08
Other	937	5	2	0	944	0.053	0.06

Table 19
Trend in occupational exposures in Spain from 1989 to 1995
[H8]

Occupational category	*Total number of workers*		*Average annual individual dose (mSv)*		*Collective dose (man Sv)*		*Number of individual dose >20 mSv*	
	1989	*1995*	*1989*	*1995*	*1989*	*1995*	*1989*	*1995*
Medical uses of radiation								
Diagnostic radiology	33 036	41 583	0.82	0.53	26.4	19.7		15
Radiotherapy	1 041	1 614	0.91	0.57	0.9	0.9		1
Nuclear medicine	924	1 546	1.93	1.35	1.6	2.0		1
Dental radiology	1 294	4 631	1.29	0.60	1.6	2.1		2
Other	-	7 196	-	0.42	-	2.7		3
Total	37 750	56 570	0.86	0.55	47	27.4	90	22
Industrial uses of radiation								
Radiography	650	440	1.10	2.46	0.6	0.7		0
Gammagraphy	169	327	4.52	2.59	0.7	0.7		4
Process control	672	1 871	1.58	0.99	0.9	1.6		2
Metrology		350		1.32		0.1		0
Manufacturing		1 045		1.14		1.1		0
Other		1 037		1.26		1.1		7
Total	3 031	5 070	1.6	1.3	5.3	5.6	17	13
Nuclear fuel cycle								
Reactor operation	10 807	8 765	2.7	3.1	20.6	16.0	88	93
Other fuel cycle operation	757	807	1.2	0.3	0.6	0.1	0	0
Research/transport	-	4 778	-	0.7	-	2.7	-	4
Total	11 564	14 350	1.8	1.3	21.2	18.8	88	97
All uses of radiation								
Total	52 345	75 990			73.5	51.8	195	132

Table 20
Medical occupational exposures in France in 1995
[C3]

Occupational category	*Monitored workers*	*Collective dose (man Sv)*	*Individual dose >20 mSv a^{-1}*	*Individual dose >50 mSv a^{-1}*
Radiology	86 607	13.0	104	31
Radiotherapy	8 528	2.0	11	1
Nuclear medicine	3 998	1.5	3	0
In vitro unsealed sources	4 669	0.09	0	0
Dental radiology	19 759	1.0	6	3
Occupational medicine	6 172	0.39	1	1
Veterinary uses	2 959	0.27	2	1
Total	132 692	18.3	127	37

Table 21
Exposures to medical staff involved in radiotherapy in the United Kingdom in 1991
[H3]

Occupational group	*Numbers of workers in dose range*				*Total number of workers*	*Annual collective dose (man Sv)*	*Average annual dose (mSv)*
	0–1 mSv	*1–5 mSv*	*5–10 mSv*	*>10 mSv*			
Beam radiographers	541	15	0	0	556	0.038	0.07
Radiotherapists	192	6	0	0	198	0.019	0.09
Sealed-source technicians	8	1	0	0	9	0.001	0.12
Radiotherapy theatre nurses	9	1	0	0	10	0.003	0.28
Brachytherapy ward nurses	548	5	3	0	556	0.053	0.10
Other nurses	203	9	1	0	213	0.051	0.24
Technicians	130	1	0	0	131	0.008	0.06
Other	354	6	0	0	360	0.028	0.08

Table 22
Exposures to workers from industrial uses of radiation [a]

Country / area	*Period*	*Monitored workers* (thousands)	*Measurably exposed workers* (thousands)	*Annual collective effective dose* (man Sv)	*Average annual effective dose (mSv)*		*Distribution ratio [b] (number of workers)*				*Distribution ratio (collective dose)*			
					Monitored workers	*Measurably exposed workers*	NR_{15}	NR_{10}	NR_5	NR_1	SR_{15}	SR_{10}	SR_5	SR_1
Industrial irradiation [c]														
Argentina	1990–1994	0.03	0.03	0.03	1.14	1.28	0.01	0.03	0.03	0.25	0.13	0.31	0.31	0.69
Australia	1990–1994	1.23	0.43	0.35	0.29	0.81	0.00	0.00	0.01	0.05	0.38	0.40	0.57	0.87
Canada	1990–1994	0.01	< 0.01	0.00	0.05	0.21	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
China	1992–1994	0.10	0.09	0.10	1.03	1.06	0.00	0.01	0.01	0.15	0.00	0.01	0.01	0.55
Cuba	1990–1994	0.03	0.03	0.04	1.27	1.29	0.00	0.00	0.00	0.41	0.00	0.00	0.00	0.68
Ecuador	1993–1994	0.01	0	0.00	0.00		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Finland [d]	1990–1994	0.76	0.04	0.06	0.08	1.54	0.00	0.00	0.00	0.02	0.00	0.07	0.36	0.82
Iceland	1990–1994	0.02	0		0.00		0.00	0.00	0.00	0.00				
Ireland	1991–1994	0.05	0.01	0.00	0.01	0.02	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Japan	1990–1994	54.9	1.79	4.95	0.09	2.76	0.00	0.00	0.00	0.01	0.43	0.55	0.74	0.93
Mexico	1990–1994	0.06		0.03	0.48									
Netherlands	1990–1994	0.01	< 0.01		0.00	0.14	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Poland	1992–1994	0.02	0.02	0.02	0.84	0.86	0.00	0.00	0.00	0.50	0.00	0.00	0.00	0.60
Sri Lanka	1994	0.02	0.01	0.00	0.09	0.15	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Syrian Arab Republic	1994	0.01	< 0.01	0.01	0.42	1.40	0.00	0.00	0.00	0.09	0.00	0.00	0.00	0.64
Total reported data [e]	1990–1994	57.2	2.45	5.96	0.10	2.28	0.00	0.00	0.00	0.01	0.41	0.52	0.70	0.91
Industrial radiography														
Argentina	1985–1989	0.05	0.01	0.03	0.59	2.7								
	1990–1994	0.33	0.09	0.27	0.83	2.90	0.01	0.02	0.04	0.14	0.30	0.41	0.56	0.92
Australia	1985–1989	0.40	0.26	0.40	1.01	1.52	0.01				0.11			
	1990–1994	2.51	1.02	0.47	0.19	0.46	0.00	0.00	0.01	0.04	0.04	0.12	0.29	0.73
Brazil [f]	1985–1989				3.30	14.5								
	1990–1994	0.90	0.41	1.26	1.40	3.13	0.01	0.02	0.06	0.27	0.32	0.39	0.59	0.94
Bulgaria [g]	1990–1994	0.69	0.17	0.60	0.87	1.63	0.00	0.00	0.01	0.12	0.03	0.04	0.08	0.35
Canada	1975–1979	1.07	0.71	4.33	4.05	6.08	0.08				0.51			
	1980–1984	1.46	0.76	4.88	3.35	6.41	0.06				0.50			
	1985–1989	1.43	0.84	6.47	4.51	7.75	0.09				0.57			
	1990–1994	2.23	1.30	7.55	3.39	5.82	0.06	0.11	0.21	0.41	0.42	0.60	0.83	0.98
China	1990–1994	2.75	2.38	3.47	1.26	1.45	0.01	0.02	0.05	0.20	0.19	0.31	0.44	0.71
China, Taiwan Province	1985–1989	1.01		1.53	1.52									
	1990–1994	2.39	1.09	0.91	0.38	0.84								

Table 22 (continued)

Country / area	*Period*	*Monitored workers* (thousands)	*Measurably exposed workers* (thousands)	*Annual collective effective dose* (man Sv)	*Average annual effective dose (mSv)*		*Distribution ratio* [b] *(number of workers)*				*Distribution ratio (collective dose)*			
					Monitored workers	*Measurably exposed workers*	NR_{15}	NR_{10}	NR_{5}	NR_{1}	SR_{15}	SR_{10}	SR_{5}	SR_{1}
Croatia	1990–1994	0.04	0.02	0.05	1.43	2.50								
Cuba	1990–1994	0.20	0.20	0.24	1.25	2.08	0.00	0.00	0.02	0.36	0.03	0.04	0.09	0.44
Czech Republic	1975–1979	0.54		1.24	2.31		0.03				0.31			
	1980–1984	1.03		2.19	2.12		0.02				0.16			
	1985–1989	1.32		2.15			0.01				0.14			
	1990–1994	1.12	0.88	1.75	1.56	1.98	0.01	0.03	0.09	0.41	0.10	0.24	0.50	0.89
Denmark	1975–1979	0.24		0.23	0.98		0.00				0.08			
	1980–1984	0.33		0.43	1.33		0.00				0.12			
	1985–1989	0.41		0.48	1.19		0.00				0.08			
	1990–1994	0.39	0.21	0.40	1.03	1.93	0.00	0.01	0.06	0.27	0.03	0.11	0.41	0.90
Ecuador	1993–1994	0.02	0.01	0.03	1.16	2.36	0.00	0.00	0.04	0.38				
Finland	1980–1984		0.03	0.05		1.51								
	1985–1989		0.06	0.11		1.65								
	1990–1994	0.35	0.09	0.09	0.26	1.02	0.00	0.00	0.00	0.07	0.07	0.10	0.16	0.67
France	1975–1979	1.28		1.47	1.15						0.03			
	1985–1989	1.60	0.09	0.28	0.18	3.11	0.00							
Gabon	1992–1994	0.00	0.00	0.08	20.48	20.48	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Germany [h]	1980–1984	2.09	0.43	0.83	0.40	1.93	0.00			0.17				
	1985–1989	6.82	2.04	7.93	1.16	3.89	0.02			0.30				
	1990–1994	6.66	2.19	9.41	1.41	4.29	0.02	0.04	0.09	0.21	0.30	0.48	0.73	0.96
Greece	1990–1994	0.24	0.03	0.06	0.26	2.50	0.00	0.00	0.01	0.05	0.20	0.34	0.61	0.90
Hungary	1975–1979	1.13	0.41	2.54	2.25	6.13	0.03				0.40			
	1980–1984	1.24	0.39	1.47	1.19	3.79	0.01				0.22			
	1985–1989	1.16	0.37	1.15	0.99	3.14	0.01				0.13			
	1990–1994	0.76	0.23	0.64	0.84	2.78	0.01	0.01	0.05	0.19	0.09	0.21	0.50	0.92
Iceland	1990–1994	0.01	0.00	0.00	0.04	0.14	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
India	1980–1984	2.93	1.39	9.0	3.07	6.50	0.06				0.55			
	1985–1989	4.23	2.12	13.2	3.12	6.10	0.06				0.54			
	1990–1994	3.68	1.92	6.77	1.84	3.49	0.03	0.05	0.10	0.27	0.37	0.53	0.73	0.95

Table 22 (continued)

Country / area	*Period*	*Monitored workers* (thousands)	*Measurably exposed workers* (thousands)	*Annual collective effective dose* (man Sv)	*Average annual effective dose (mSv)*		*Distribution ratio* [b] *(number of workers)*				*Distribution ratio (collective dose)*			
					Monitored workers	*Measurably exposed workers*	NR_{15}	NR_{10}	NR_{5}	NR_{1}	SR_{15}	SR_{10}	SR_{5}	SR_{1}
Indonesia	1980–1984 1985–1989 1990–1994	0.14 0.43	0.02 0.03	0.22 0.40	1.53 0.95	10.8 14.9	0.03 0.06				0.45 0.10			
Ireland	1980–1984 1985–1989 1990–1994	0.07 0.05 0.09	0.04 0.03 0.02	0.05 0.06 0.03	0.75 1.41 0.35	1.39 2.57 1.58	0.01 0.00	0.00	0.03	0.12	0.15 0.00	0.00	0.35	0.79
Japan	1980–1984 1985–1989 1990–1994	3.31 2.83 4.35	1.58 1.08 1.41	5.67 3.35 4.00	1.71 1.19 0.83	3.59 3.09 2.57	0.02 0.01 0.01	0.02	0.05	0.15	0.24	0.38	0.62	0.93
Kuwait	1992–1994	0.13	0.03	0.60	0.47	1.98	0.00	0.00	0.02	0.10	0.00	0.00	0.28	0.72
Mexico	1985–1989 1990–1994	0.82 0.87	0.49	5.10 4.83	6.23 5.58	10.5	0.10				0.67			
Myanmar	1994	0.00	0.00	0.00	0.75	0.75	0.00	0.00	0.00	0.50				
Netherlands [i]	1980–1984 1985–1989 1990–1994	0.97 1.02 1.00	0.64	0.34 0.48 1.52	0.35 0.47 1.52	2.38	0.00 0.00 0.01	0.02	0.07	0.33	0.13 0.20 0.19	0.25	0.50	0.92
New Zealand	1980–1984	0.15		0.35	2.33									
Norway	1980–1984 1985–1989 1990–1994	0.80 0.82 1.11	0.44 0.40 0.26	0.79 0.62 0.31	0.99 0.76 0.28	1.81 1.56 1.19	0.00 0.00 0.00	0.00	0.01	0.09	0.04 0.10			
Pakistan	1990–1994	0.11	0.10	0.58	5.19	5.92	0.13	0.17	0.24	0.48	0.67	0.74	0.85	0.96
Peru	1994	0.04	0.03	0.18	5.00	6.73	0.00	0.00	0.11	0.20				
Poland	1992–1994	0.80	0.77	2.36	2.96	3.07	0.03	0.05	0.11	0.86	0.24	0.36	0.49	0.97
Slovakia	1990–1994	0.47	0.26	0.56	1.19	2.08	0.00	0.01	0.04	0.32	0.04	0.09	0.32	0.88
Slovenia	1993–1994	0.09	0.09	0.11	1.29	1.30	0.01	0.02	0.06	0.25	0.15	0.22	0.46	0.77
South Africa	1975–1979 1980–1984 1985–1989	0.57 0.75 0.72	0.31 0.45 0.32	0.11 2.38 1.68	0.19 3.18 2.33	0.35 5.30 5.29	0.05 0.03				0.44 0.36			

Table 22 (continued)

Country / area	*Period*	*Monitored workers (thousands)*	*Measurably exposed workers (thousands)*	*Annual collective effective dose (man Sv)*	*Average annual effective dose (mSv)*		*Distribution ratio [b] (number of workers)*				*Distribution ratio (collective dose)*			
					Monitored workers	*Measurably exposed workers*	NR_{15}	NR_{10}	NR_5	NR_1	SR_{15}	SR_{10}	SR_5	SR_1
Spain	1985–1989	0.82	0.66	1.23	1.50	1.87	0.02				0.32			
Sri Lanka	1990–1994	0.03	0.01	0.03	1.00	2.12	0.01	0.02	0.03	0.12	0.49	0.70	0.73	0.92
Sweden	1975–1979 1980–1984 1985–1989	0.77 0.66 0.64	0.19 0.17 0.25	0.49 0.38 0.28	0.63 0.57 0.43	2.56 2.27 1.12	0.01 0.00 0.00				0.16 0.06 0.15			
Syrian Arab Republic	1990–1994	0.06	0.01	0.01	0.20	1.36	0.00	0.00	0.00	0.02	0.00	0.00	0.11	0.37
Thailand	1990–1994	2.28	0.23	1.77	0.78	7.85	0.02	0.02	0.03	0.06	0.70	0.80	0.90	0.99
United Kingdom [j]	1980–1984 1985–1989 1990–1994	1.82 4.82 5.10	 4.08 2.49	3.60 5.67 3.86	1.98 1.18 0.76	 1.39 1.55	0.02 0.01 0.01	 0.01	 0.03	 0.11	 0.43			
United Rep. of Tanzania [k]	1990–1994	0.03	0.02	0.08	2.46	3.56	0.00	0.01	0.19	0.43	0.00	0.03	0.47	0.90
United States [l]	1975–1979 1980–1984 1985–1989 1990–1994	17 27 23 5.60	 12 3.75	50 80 39 18.3	2.94 2.96 1.70 3.27	 3.25 5.68	 0.03	 0.10	 0.20	 0.42	 0.29	 0.60	 0.82	 0.98
USSR	1975–1979 1980–1984 1985–1989	2.27 2.53 2.63		30.0 20.2 17.2	13.2 7.98 6.55									
Total of reported data [m]	1975–1979 1980–1984 1985–1989 1990–1994	24.0 42.1 49.9 47.4	 22.67	89.5 125 98.7 73.2	3.74 2.98 1.98 1.54	 3.23	0.04 0.03 0.03 0.02	 0.04	 0.08	 0.23	0.39 0.42 0.44 0.30	 0.49	 0.70	 0.93
World [n]	1975–1979 1980–1984 1985–1989 1990–1994	72 116 108 106	 53	190 230 160 170	2.61 1.98 1.44 1.58	 3.17	0.01	0.03	0.07	0.27	0.23	0.36	0.57	0.89
Luminizing [c]														
Canada	1990–1994	0.02	0.01	0.01	0.54	1.17	0.00	0.00	0.00	0.18	0.00	0.00	0.00	0.73
China	1992	0.04	0.04	0.01	0.28	0.28	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Table 22 (continued)

Country / area	*Period*	*Monitored workers* (thousands)	*Measurably exposed workers* (thousands)	*Annual collective effective dose* (man Sv)	*Average annual effective dose (mSv)*		*Distribution ratio* [b] *(number of workers)*				*Distribution ratio (collective dose)*			
					Monitored workers	*Measurably exposed workers*	NR_{15}	NR_{10}	NR_5	NR_1	SR_{15}	SR_{10}	SR_5	SR_1
France	1975–1979 1980–1984 1985–1989 1990–1994	0.07 0.04 0.03		0.38 0.24 0.18	5.30 5.52 6.84		0.14 0.17				0.66 0.55 0.52			
India [o]	1980–1984 1985–1989 1990–1994	0.07 0.15	0.03 0.06	0.08 0.19	1.16 1.26	2.78 3.37	0.01 0.02				0.16 0.54			
South Africa [p]	1990–1994	0.02	0.02	0.01	0.88	0.96	0.00	0.00	0.04	0.22	0.00	0.00	0.28	0.78
Switzerland	1975–1979 1980–1984 1985–1989	0.21 0.13 0.16		2.31 1.02 0.68	11.2 7.82 4.31		0.25 0.14 0.04				0.53 0.39 0.18			
United Kingdom (paint) United Kingdom (tritium)	1975–1979 1975–1979 1980–1984	0.09 0.25 0.33		0.40 1.50 1.10	4.32 5.89 3.33		0.12 0.06				0.65 0.40			
Total reported data [m]	1975–1979 1980–1984 1985–1989 1990–1994	0.51 0.27 0.54 0.08		3.77 1.34 1.45 0.03	7.44 5.01 2.71 0.38		0.18 0.08 0.03 0.00	0.00	0.01	0.10	0.58 0.37 0.31 0.00	0.00	0.09	0.50
Radioisotope production														
Argentina	1975–1979 1980–1984 1985–1989 1990–1994	0.17 0.22 0.18 0.16	0.14	0.67 0.45 0.44 0.38	4.05 2.10 2.47 2.47	2.69	0.02	0.04	0.12	0.52	0.22	0.31	0.49	0.93
Australia	1990–1994	0.09		0.26	2.99		0.03	0.09	0.27		0.18	0.52	0.93	
Canada [q]	1975–1979 1980–1984 1985–1989 1990–1994	0.05 0.03 0.30 0.40	0.03 0.03 0.16 0.23	0.12 0.19 0.48 0.57	2.67 5.83 1.61 1.44	3.84 7.28 2.94 2.45	0.02 0.09 0.01 0.00	0.02	0.08	0.35	0.14 0.41 0.18 0.05	0.17	0.48	0.93
China	1990–1994	0.35	0.32	1.43	4.10	4.46	0.07	0.12	0.21	0.50	0.50	0.63	0.80	096
Czech Republic	1975–1979 1980–1984 1985–1989 1990–1994	0.18 0.33 0.40 0.10	0.08	0.50 0.60 0.81 0.09	2.76 1.80 2.05 0.89	1.14	0.02 0.02 0.04 0.00	0.00	0.03	0.32	0.19 0.30 0.42 0.00	0.00	0.18	0.72

Table 22 (continued)

Country / area	*Period*	*Monitored workers* (thousands)	*Measurably exposed workers* (thousands)	*Annual collective effective dose* (man Sv)	*Average annual effective dose (mSv)*		*Distribution ratio* [b] *(number of workers)*				*Distribution ratio (collective dose)*			
					Monitored workers	*Measurably exposed workers*	NR_{15}	NR_{10}	NR_{5}	NR_{1}	SR_{15}	SR_{10}	SR_{5}	SR_{1}
Finland [r]	1975–1979		0.00	0.01		4.23								
	1980–1984		0.00	0.02		3.92								
	1985–1989		0.01	0.05		4.10								
	1990–1994													
Hungary	1975–1979	0.21	0.08	0.27	1.33	3.49	0.01				0.21			
	1980–1984	0.25	0.09	0.30	1.18	3.35	0.01				0.10			
	1985–1989	0.24	0.09	0.32	1.31	3.56	0.01				0.16			
	1990–1994	0.10	0.05	0.16	1.55	2.97	0.00	0.01	0.09	0.37	0.02	0.10	0.47	0.94
India	1980–1984	0.40	0.31	0.67	1.69	2.20	0.01				0.17			
	1985–1989	0.51	0.35	0.71	1.39	2.02	0.01				0.14			
	1990–1994	0.53	0.37	0.73	1.39	1.98	0.01	0.03	0.07	0.28	0.23	0.33	0.52	0.85
Indonesia	1975–1979	0.03		0.11	4.34									
	1980–1984	0.03	0.03	0.06	1.76	2.03								
	1985–1989	0.05	0.04	0.08	1.81	2.10								
	1990–1994													
Netherlands [i]	1985–1989	0.18		0.87	4.97		0.04				0.13			
	1990–1994	0.21	0.19	0.94	4.41	4.85	0.05	0.13	0.36	0.65	0.21	0.42	0.79	0.97
Pakistan	1990–1994	0.02	0.02	0.04	1.81	1.82	0.00	0.03	0.03	0.61	0.00	0.09	0.30	0.83
Peru	1994	0.03	0.02	0.13	5.00	5.21	0.08	0.20	0.32	0.84				
Poland	1992–1994	0.20	0.19	0.27	1.39	1.46	0.00	0.01	0.03	0.78	0.04	0.07	0.21	0.92
Republic of Korea	1975–1979	0.02	0.02	0.12	5.22	6.00	0.10				0.32			
	1980–1984	0.02	0.02	0.15	7.43	7.65	0.34				0.64			
	1985–1989	0.02	0.01	0.09	5.38	6.52	0.06				0.17			
South Africa	1975–1979	0.02		0.16	8.74		0.23				0.71			
	1980–1984	0.30		0.16	5.27		0.10				0.57			
	1985–1989	0.03		0.18	5.75		0.12				0.52			
	1990–1994	0.10	0.06	0.26	2.55	5.63	0.04	0.09	0.15	0.35	0.28	0.69	0.82	0.96
Thailand	1990–1994	0.04	0.03	0.04	1.15	1.48	0.00	0.01	0.02	0.43	0.00	0.06	0.12	0.81
United Kingdom	1975–1979	0.97		6.39	6.59		0.14							
	1980–1984	1.26		4.82	3.84		0.07							
	1985–1989	1.72		4.63	2.70		0.03							
	1991	1.22		2.40	1.96									

Table 22 (continued)

Country / area	*Period*	*Monitored workers* (thousands)	*Measurably exposed workers* (thousands)	*Annual collective effective dose* (man Sv)	*Average annual effective dose (mSv)*		*Distribution ratio* [b] *(number of workers)*				*Distribution ratio (collective dose)*			
					Monitored workers	*Measurably exposed workers*	NR_{15}	NR_{10}	NR_{5}	NR_{1}	SR_{15}	SR_{10}	SR_{5}	SR_{1}
United States	1975–1979	20		40	2.00									
	1980–1984	29		30	1.03									
	1985–1989	30	17	25	0.83	1.47								
	1990–1994	4.45	2	6.92	1.56	4.69	0.02	0.05	0.07	0.16	0.49	0.75	0.88	0.97
Total reported data [m]	1975–1979	21.6		48.3	2.23		0.10				0.18			
	1980–1984	31.5		37.3	1.18		0.05				0.23			
	1985–1989	33.2		32.7	0.98		0.03				0.23			
	1990–1994	7.98	4.46	14.6	1.83	3.28	0.02	0.05	0.09	0.25	0.39	0.60	0.78	0.95
World [n]	1975–1979	57		130	2.25									
	1980–1984	82		100	1.26									
	1985–1989	88		98	1.12									
	1990–1994	24	16	47	1.93	2.95	0.02	0.04	0.10	0.41	0.25	0.42	0.64	0.94
Well–logging [c]														
Australia	1990–1994	4.71	1.66	0.17	0.04	0.10	0	0	0	0	0	0	0.02	0.10
Canada	1975–1979	0.45	0.21	0.52	1.16	2.43	0.01				0.17			
	1980–1984	1.01	0.58	1.28	1.27	2.21	0.01				0.11			
	1985–1989	1.11	0.74	1.37	1.24	1.85	0.00				0.05			
	1990–1994	0.95	0.58	0.94	0.99	1.90	0.00	0.00	0.03	0.30	0.08	0.11	0.30	0.85
China	1990–1994	0.34	0.34	0.48	1.40	1.41	0.01	0.01	0.02	0.56	0.15	0.19	0.23	0.86
Croatia	1990–1994	0.08	0.01	0.01	0.13	1.00								
Cuba	1990–1994	0.08	0.08	0.12	1.60	1.60	0.00	0.00	0.00	0.70	0.00	0.00	0.00	0.88
Czech Republic	1975–1979	0.06		0.06	1.02									
	1980–1984	0.09		0.15	1.60		0.00				0.03			
	1985–1989	0.11		0.20	1.72		0.00				0.02			
	1990–1994	0.12	106	0.24	2.05	2.26	0.00	0.01	0.08	0.73	0.00	0.07	0.26	0.96
Ecuador	1993–1994	0.11	0.11	0.16	1.45	1.45	0.00	0.00	0.01	.066				
Iceland	1990–1994	0.01	0.00		0.00		0.00	0.00	0.00	0.00				
India [s]	1980–1984	0.19	0.04	0.07	0.38	1.75	0.01				0.39			
	1985–1989	0.64	0.30	0.38	0.54	1.25	0.00				0.09			
	1990–1994	0.87	0.51	0.45	0.51	0.87	0.00	0.00	0.01	0.15	0.02	0.05	0.15	0.65

Table 22 (continued)

Country / area	*Period*	*Monitored workers* (thousands)	*Measurably exposed workers* (thousands)	*Annual collective effective dose* (man Sv)	*Average annual effective dose (mSv)*		*Distribution ratio* [b] *(number of workers)*				*Distribution ratio (collective dose)*			
					Monitored workers	*Measurably exposed workers*	NR_{15}	NR_{10}	NR_5	NR_1	SR_{15}	SR_{10}	SR_5	SR_1
Indonesia	1980–1984 1985–1989	0.14 0.56	0.04 0.45	0.12 0.84	0.82 1.51	3.07 1.89								
Kuwait	1992–1994	0.03	0.00	0.01	0.20	3.2	0.00	0.00	0.01	0.01	0.00	0.00	0.45	0.45
Mexico	1985–1989 1990–1994	0.36 0.48	0.01	0.00 0.07	0.01 0.15	0.32								
Myanmar	1994	0.00	0.00	0.00	0.65	0.65	0.00	0.00	0.00	0.50				
Norway	1990–1992	0.35	0.03	0.00	0.01	0.15	0.00	0.00	0.00	0.00				
Peru	1994	0.10	0.09	0.04	0.40	0.45	0.00	0.00	0.00	0.00				
Poland	1992–1994	0.16	0.15	0.15	0.97	1.01	0.00	0.00	0.01	0.81	0.00	0.02	0.06	0.90
Slovakia	1990–1994	0.04	0.03	0.22	5.25	8.55	0.09	0.27	0.43	0.57	0.29	0.70	0.90	0.99
Slovenia	1993–1994	0.00	0.00	0.00	1.54	1.54	0.00	0.00	0.00	0.67				
South Africa	1975–1979 1980–1984 1985–1989	0.04 0.04 0.04	0.01 0.02 0.01	0.00 0.06 0.05	0.01 1.61 1.49	0.03 3.76 4.55								
United States [t]	1975–1979	7.6		10.3	1.36						0.3			
Total reported data [m]	1975–1979 1980–1984 1985–1989 1990–1994	 8.43	 3.87	 3.06	1.32 1.17 1.07 0.36	 0.79	0.01 0.00 0.00 0.00	 0.00	 0.01	 0.12	0.27 0.10 0.04 0.08	 0.14	 0.27	 0.79
Accelerator operation [c]														
Argentina	1990–1994	0.03	0.02	0.00	0.09	0.12	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Canada	1975–1979 1980–1984 1985–1989 1990–1994	0.58 0.88 1.00 0.99	0.19 0.23 0.53 0.40	0.17 0.40 1.06 0.77	0.30 0.45 1.06 0.77	0.91 1.76 2.00 1.94	0.00 0.00 0.00 0.00	 0.01	 0.05	 0.17	0.10 0.04 0.07 0.03	 0.10	 0.50	 0.89
China	1990–1994	0.02	0.00	0.02	1.04	1.71	0.00	0.00	0.05	0.26	0.00	0.00	0.37	0.91
Ecuador	1993–1994	0.01	0	0.00	0.00		0.00	0.00	0.00	0.00				

Table 22 (continued)

Country / area	*Period*	*Monitored workers* (thousands)	*Measurably exposed workers* (thousands)	*Annual collective effective dose* (man Sv)	*Average annual effective dose (mSv)*		*Distribution ratio* [b] *(number of workers)*				*Distribution ratio (collective dose)*			
					Monitored workers	*Measurably exposed workers*	NR_{15}	NR_{10}	NR_{5}	NR_{1}	SR_{15}	SR_{10}	SR_{5}	SR_{1}
Finland	1980–1984		0.01	0.01		1.23								
	1985–1989		0.01	0.01		1.23								
	1990–1994	0.08	0.01	0.01	0.08	1.21	0.00	0.00	0.00	0.04	0.00	0.00	0.00	0.83
Netherlands	1980–1984	0.18	0.01	0.01	0.03	0.67								
	1985–1989	0.16	0.01	0.00	0.03	0.46								
Poland	1992–1994	0.14	0.13	0.14	0.95	1.04	0.00	0.00	0.01	0.48	0.05	0.09	0.11	0.68
Slovakia	1990–1994	0.02	0.01	0.04	1.68	2.70	0.00	0.02	0.11	0.33	0.00	0.12	0.47	0.89
Slovenia	1990–1994	0.01	0.01	0.00	0.51	0.51	0.00	0.00	0.00	0.02	0.00	0.00	0.00	0.04
South Africa	1975–1979	0.07	0.03	0.03	0.46	1.00								
	1980–1984	0.10	0.04	0.27	2.72	6.59	0.05				0.55			
	1985–1989	0.22	0.07	0.34	1.56	4.76	0.04				0.61			
United Kingdom [u]	1985–1989	0.50		0.25	0.50									
	1990–1994													
United States [t]	1975–1979	3.96	1.73	7.19	1.82	4.16								
	1980–1984	3.92	1.44	3.07	0.78	2.12								
	1985–1989	4.25	1.66	2.07	0.49	1.24								
	1990–1994													
Total reported data [m]	1975–1979	4.50		7.38	1.62		0.00				0.12			
	1980–1984	4.93		3.73	0.76		0.00				0.26			
	1985–1989	5.72		3.52	0.62		0.01				0.19			
	1990–1994	1.31	0.58	0.98	0.75	1.68	0.00	0.01	0.04	0.19	0.03	0.09	0.42	0.83
All other industrial uses [c]														
Australia	1990–1994	2.90	1.14	0.58	0.20	0.60	0.00	0.00	0.00	0.04	0.29	0.31	0.48	0.77
Brazil	1990–1994	0.53	0.03	0.21	0.39	8.26	0.00	0.00	0.00	0.01	0.89	0.90	0.92	0.96
Bulgaria	1990–1994	0.14		0.14	1.04									
China	1990–1994	1.16	1.06	1.29	1.11	1.22	0.00	0.01	0.04	0.22	0.13	0.23	0.34	0.74
China, Taiwan Province	1990–1994	2.29	0.65	0.56	0.25	0.86								
Croatia	1990–1994	0.15	0.05	0.01	0.07	0.20								
Cuba	1991–1994	0.02	0.02	0.01	0.34	0.34	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Czech Republic	1991–1994	0.99	0.75	0.77	0.78	1.04	0.00	0.00	0.02	0.17	0.01	0.03	0.16	0.45
Denmark	1990–1994	2.37	0.30	0.12	0.05	0.42	0.00	0.00	0.00	0.01	0.06	0.06	0.23	0.48
Ecuador	1993–1994	0.03	0.03	0.06	2.63	2.63	0.02	0.04	0.08	0.84				

Table 22 (continued)

Country / area	*Period*	*Monitored workers* (thousands)	*Measurably exposed workers* (thousands)	*Annual collective effective dose* (man Sv)	*Average annual effective dose (mSv)*		*Distribution ratio* [b] *(number of workers)*				*Distribution ratio (collective dose)*			
					Monitored workers	*Measurably exposed workers*	NR_{15}	NR_{10}	NR_{5}	NR_{1}	SR_{15}	SR_{10}	SR_{5}	SR_{1}
Germany [h]	1990–1994	45.2	14.4	38.5	0.85	2.67	0.01	0.02	0.05	0.15	0.21	0.37	0.61	0.91
Hungary	1990–1994	1.38	0.04	0.05	0.04	1.16	0.00	0.00	0.00	0.01	0.11	0.11	0.25	0.66
Japan	1990–1994	60.7	3.29	7.52	0.12	2.29	0.00	0.00	0.01	0.02	0.27	0.37	0.55	0.88
Kuwait	1992–1994	0.03	0.00	0.01	0.11	0.4	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Mexico	1990–1994	0.30		0.27	0.91									
Netherlands	1990–1994	2.88	0.55	0.22	0.08	0.37	0.00	0.00	0.00	0.01	0.05	0.10	0.18	0.47
Norway	1990–1992	0.86	0.03	0.02	0.02	0.62	0.00	0.00	0.00	0.04				
Peru	1994	0.10	0.09	0.05	0.50	0.55	0.00	0.00	0.00	0.00				
Poland	1992–1994	0.93	0.84	0.89	0.96	1.01	0.00	0.00	0.01	0.63	0.00	0.01	0.03	0.80
Slovakia	1990–1994	0.35	0.07	0.09	0.26	1.36	0.00	0.00	0.00	0.09	0.06	0.06	0.08	0.77
Slovenia	1993–1994	0.71	0.48	0.19	0.27	0.40	0.00	0.00	0.00	0.02	0.07	0.07	0.07	0.15
Sri Lanka	1990–1994	0.01	0.00	0.01	0.83	2.46	0.02	0.03	0.06	0.08	0.48	0.67	0.89	0.91
Sweden	1990–1994	1.09		0.48	0.44									
Switzerland	1990–1994	2.77		0.33	0.12		0.00	0.00	0.01	0.02	0.18	0.29	0.56	0.88
Russian Federation	1992–1994	2.99	2.99	6.08	2.03		0.00				0.04			
United Kingdom	1990–1994	13.3	7.14	6.78	0.51	0.95	0.00	0.00	0.02	0.10				
Total reported data [m]	1990–1994	143	34.4	65.1	0.45	1.89	0.00	0.01	0.02	0.07	0.21	0.34	0.56	0.86

a Data are annual averages over the periods indicated.
b The values of NR are for the monitored workforce.
c Insufficient data are available for these categories to enable a reliable estimate of worldwide exposure.
d Reported data contain a contribution from industrial radiography.
e The total for measurably exposed workers has been rationed up to take account of countries that did not report the number of measurably exposed workers, but did report a figure for monitored workers.
f Reported data relate to approximately 25% of monitored workers.
g Reported data contain a contribution from industrial irradiation.
h Within the data from 1990–1994, the data concerning 1990 only relate to the Federal Republic of Germany. Earlier data is that combined from the German Democratic Republic and the Federal Republic of Germany.
i The reported data (covering about 80% of the workforce) have been scaled to represent the whole country.
j Data for 1980–1984 include only those workers whose dose records are held within the Dosemeter Issue and Record Keeping (DIRK) service of the NRPB. The total number of radiographers in the United Kingdom is somewhat larger. Data for 1985–1989 are for classified workers only.
k Reported data contain a contribution from other industrial uses (gauges).
l Calculation of SR distribution ratios based on data from 1993 and 1994.
m These data should be interpreted with care, particularly because the countries included in the summations for the representative five-year periods may not be the same, depending on whether data were reported for the period in question. Consequently, direct comparison of data for different periods is invalid to the extent that the data comprise contributions from different countries. It should also be noted that the data on NR_{15} and SR_{15} are averages of data reported on these ratios. In general, these data are less complete than those that form the basis of the summed number of workers and collective doses.
n These values are estimated by the method detailed in Section I.E.
o The doses include exposures from tritium intake and external radiation from promethium-147.
p All reported doses are from internal exposure only.
q Before 1989 radioisotope production was undertaken by Atomic Energy of Canada Limited, and separate statistics of this group of workers are not available. The average data tabulated for 1985–1989 are those for 1989, when production was transferred from Atomic Energy of Canada Limited; this accounts for the significant difference compared with the previous period. The contribution of internal exposure is small.
r Internal exposure included after 1986; it amounted to about 50%.
s Neutrons contribute about 15%–25% to the reported doses.
t Data are for licensees of the United States Department of Energy only. The effective doses include a neutron component.

Table 23
Reported exposures to workers from industrial uses of radiation (1990–1994) [a]

Region	*Monitored workers*	*Measurably exposed workers* [b]	*Annual collective effective dose (man Sv)*	*Average annual effective dose (mSv)*		*Distribution ratio* [c] *(number of workers)*				*Distribution ratio (collective dose)*			
				Monitored workers	*Measurably exposed workers*	NR_{15}	NR_{10}	NR_5	NR_1	SR_{15}	SR_{10}	SR_5	SR_1
Industrial irradiation													
East and South-East Asia	95	91	0.10	1.03	1.06	0.00	0.01	0.01	0.15	0.00	0.01	0.01	0.55
Eastern Europe	19	19	0.02	0.84	0.86	0.00	0.00	0.00	0.50	0.00	0.00	0.00	0.60
Indian subcontinent	15	9	0.00	0.09	0.15	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Latin America	64	56	0.07	1.09	1.25	0.00	0.01	0.01	0.31	0.06	0.13	0.13	0.68
OECD except United States	2 073	489	0.44	0.21	0.90	0.00	0.00	0.01	0.04	0.32	0.35	0.54	0.86
Remainder	11	3	0.01	0.42	1.40	0.00	0.00	0.00	0.09	0.00	0.00	0.00	0.64
Industrial radiography													
East and South-East Asia	7 418	3 697	6.15	0.83	1.66	0.01	0.02	0.04	0.14	0.36	0.48	0.60	0.80
Eastern Europe	3 937	2 390	6.02	1.53	2.52	0.01	0.02	0.07	0.39	0.14	0.25	0.44	0.87
Indian subcontinent	3 816	2 037	7.38	1.93	3.62	0.03	0.05	0.10	0.28	0.39	0.55	0.74	0.95
Latin America	1 483	733	1.98	1.34	2.70	0.01	0.02	0.05	0.25	0.28	0.35	0.52	0.87
OECD except United States	23 695	9 800	31.99	1.35	3.26	0.02	0.03	0.07	0.18	0.30	0.46	0.70	0.95
United States	5 599	3 746	18.31	3.27	5.68	0.03	0.10	0.20	0.42	0.29	0.60	0.82	0.98
Remainder	233	56	0.77	3.45	13.75	0.02	0.02	0.06	0.14	0.10	0.11	0.37	0.76
Luminizing													
East and South-East Asia	40	40	0.01	0.28	0.28	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
OECD except United States	23	10	0.01	0.54	1.17	0.00	0.00	0.00	0.18	0.00	0.00	0.00	0.73
Remainder	16	15	0.01	0.88	0.96	0.00	0.00	0.04	0.22	0.00	0.00	0.28	0.78
Radioisotope production													
East and South-East Asia	349	321	1.43	4.10	4.46	0.07	0.12	0.21	0.50	0.50	0.63	0.80	0.96
Eastern Europe	400	316	0.52	1.30	1.65	0.00	0.01	0.05	0.56	0.03	0.07	0.28	0.89
Indian subcontinent	548	390	0.77	1.41	1.97	0.01	0.03	0.07	0.29	0.22	0.32	0.51	0.85
Latin America	181	167	0.51	2.82	3.05	0.03	0.06	0.15	0.56	0.22	0.31	0.49	0.93
OECD except United States	1 831	1 281	3.91	2.14	3.05	0.02	0.06	0.18	0.46	0.15	0.33	0.67	0.95
United States	4 444	2 003	6.92	1.56	4.69	0.02	0.05	0.07	0.16	0.49	0.75	0.88	0.97
Remainder	136	87	0.30	2.21	3.45	0.03	0.07	0.12	0.37	0.24	0.61	0.73	0.94

Table 23 (continued)

Region	*Monitored workers*	*Measurably exposed workers* [b]	*Annual collective effective dose (man Sv)*	*Average annual effective dose (mSv)*		*Distribution ratio* [c] *(number of workers)*				*Distribution ratio (collective dose)*			
				Monitored workers	*Measurably exposed workers*	NR_{15}	NR_{10}	NR_5	NR_1	SR_{15}	SR_{10}	SR_5	SR_1
Well-logging													
East and South-East Asia	346	344	0.48	1.39	1.40	0.01	0.01	0.02	0.56	0.15	0.19	0.23	0.86
Eastern Europe	320	284	0.61	1.91	2.15	0.01	0.04	0.09	0.75	0.10	0.28	0.44	0.96
Indian subcontinent	874	510	0.45	0.51	0.87	0.00	0.00	0.01	0.15	0.02	0.05	0.15	0.65
Latin America	287	275	0.32	1.11	1.16	0.00	0.00	0.00	0.44	0.00	0.00	0.00	0.88
OECD except United States	6 492	2 449	1.18	0.18	0.48	0.00	0.00	0.00	0.05	0.08	0.11	0.30	0.85
Remainder	32	1	0.01	0.20	3.20	0.00	0.00	0.01	0.01	0.00	0.00	0.45	0.45
Accelerator operation													
East and South-East Asia	22	14	0.02	1.04	1.71	0.00	0.00	0.05	0.26	0.00	0.00	0.37	0.91
Eastern Europe	176	150	0.18	1.02	1.20	0.00	0.00	0.02	0.44	0.04	0.10	0.19	0.73
Latin America	31	18	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
OECD except United States	1 076	401	0.78	0.72	1.94	0.00	0.01	0.05	0.16	0.03	0.10	0.49	0.89
All medical uses													
East and South-East Asia	3 446	1 709	1.85	0.54	1.08	0.00	0.01	0.04	0.22	0.13	0.23	0.34	0.74
Eastern Europe	6 780	4 686	8.02	1.18	1.71	0.00	0.00	0.01	0.22	0.03	0.03	0.10	0.66
Indian subcontinent	13	4	0.1	0.83	2.46	0.02	0.03	0.06	0.08	0.48	0.67	0.89	0.91
Latin America	680	164	0.33	0.49	2.01	0.00	0.00	0.01	0.07	0.85	0.86	0.88	0.92
OECD except United States	132 345	27 122	54.83	0.41	1.98	0.00	0.01	0.02	0.07	0.22	0.37	0.60	0.90
Remainder	32	1	0.01	0.11	0.40	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

a Data are annual values averaged over the period reported.
b The values for measurably exposed workers has been rationed up to take account of countries that did not report the number of measurably exposed workers, but did report a figure for monitored workers.
c Insufficient data are available for these categories to enable a reliable estimate of worldwide exposure.

Table 24
Exposures to workers from all industrial uses of radiation [a]
Data from UNSCEAR Survey of Occupational Exposures

Country / area	*Period*	*Monitored workers (thousands)*	*Measurably exposed workers (thousands)*	*Annual collective effective dose (man Sv)*	*Average annual effective dose (mSv)*		NR_{15} [b]	SR_{15}
					Monitored workers	*Measurably exposed workers*		
Argentina	1985–1989	0.07	0.03	0.85	1.29	2.74	0.03	0.61
	1990–1994	0.53	0.28	0.68	1.27	2.44	0.01	0.25
Australia	1975–1979	2.21		0.92	0.41			
	1985–1989	7.1	3.30	0.78	0.11	0.23	0.00	0.09
	1990–1994	11.43	4.29	1.83	0.16	0.43	0.00	0.17
Brazil	1985–1989	15.00	3.10	24	1.60	7.69		
	1990–1994	1.44	0.43	1.47	1.02	3.40	0.01	0.40
Bulgaria	1990–1994	0.83	0.17	0.74	0.89	3.70	0.00	0.02
Canada	1975–1979	8.06	3.60	13.2	1.63	3.66	0.02	0.42
	1980–1984	11.0	4.36	14.4	1.31	3.30	0.02	0.34
	1985–1989	10.70	4.70	16.2	1.52	3.45	0.02	0.39
	1990–1994	4.59	2.52	9.84	2.14	3.91	0.03	0.34
China	1990–1994	4.76	4.25	6.8	1.43	1.60	0.01	0.24
China, Taiwan Province	1980–1984	2.42		1.91	0.79			
	1985–1989	3.04		1.97	0.65			
	1990–1994	4.67	1.74	1.47	0.31	0.85		
Croatia	1990–1994	0.26	1.00	0.07	0.27	0.88		
Cuba	1990–1994	0.33	0.33	0.41	1.25	1.25	0.00	0.02
Czech Republic	1975–1979	1.65		2.26	1.38		0.01	0.23
	1980–1984	2.92		3.77	1.29		0.01	0.18
	1985–1989	3.62		3.77	1.04		0.01	0.21
	1990–1994	2.33	1.81	2.85	1.22	1.58	0.00	0.06
Denmark	1975–1979	0.46		0.32	0.68		0.00	0.06
	1980–1984	0.64		0.49	0.76		0.00	0.11
	1985–1989	0.80		0.52	0.65		0.00	0.07
	1990–1994	2.76	0.50	0.52	0.19	1.04	0.00	0.04
Ecuador	1990–1994	0.17	0.15	0.25	1.49	1.72	0.00	
Finland [c]	1975–1979							
	1980–1984	0.67	0.05	0.14	0.21	2.97		0.20
	1985–1989	2.09	0.15	0.26	0.12	1.75	0.00	0.05
	1990–1994	2.36	0.17	0.32	0.14	1.94	0.00	0.06
		1.19	0.13	0.16	0.13	1.20	0.00	0.04
France	1975–1979							
	1980–1984							
	1985–1989	9.9		24	2.42			
Gabon	1990–1994	0.01	0.01	0.08	20.48	20.48	1.00	1.00
Germany [d]	1985–1989	58.6	14.70	25.6	0.44	1.74	0.01	0.29
	1990–1994	51.9	16.59	47.9	0.92	2.89	0.01	0.23
Greece	1990–1994	0.24	0.03	0.06	0.26	2.50	0.00	0.20
Hungary	1975–1979	3.26	0.58	3.01	0.92	5.14	0.01	0.36
	1980–1984	3.36	0.56	1.93	0.58	3.47	0.00	0.19
	1985–1989	3.26	0.53	1.57	0.48	2.97	0.00	0.12
	1990–1994	2.25	0.33	0.85	0.38	2.60	0.00	0.08

Table 24 (continued)

Country / area	*Period*	*Monitored workers* (thousands)	*Measurably exposed workers* (thousands)	*Annual collective effective dose* (man Sv)	*Average annual effective dose (mSv)*		NR_{15} [b]	SR_{15}
					Monitored workers	*Measurably exposed workers*		
Iceland	1990–1994	0.03	<0.01	0.00	0.00	0.00	0.00	
India	1990–1994	5.08	2.80	7.95	1.57	2.84	0.02	0.34
Indonesia	1980–1984 1985–1989	0.02 0.03	0.01 0.03	0.01 0.03	0.75 1.12	1.25 1.12		
Ireland	1985–1989 1991–1994	0.74 0.13	0.06 0.23	0.08 0.03	0.11 0.23	1.37 1.32	0.00 0.00	0.09
Italy [e]	1985–1989	1.98	0.44	0.87	0.44	1.97	0.00	0.35
Japan	1975–1979 1980–1984 1985–1989 1990–1994	27.6 29.0 32.00 120	3.93 4.06 3.06 6.49	8.93 11.0 8.48 16.5	0.32 0.38 0.27 0.14	2.27 2.70 2.77 2.54	0.01 0.00 0.00 0.00	 0.31
Kuwait	1990–1994	0.19	0.03	0.62	3.26	22.96	0.00	0.00
Mexico	1985–1989 1990–1994	1.63 1.69	0.51 0.51	5.23 5.2	3.21 3.07	10.20	0.05	0.66
Myanmar	1990–1994	0.01	0.01	0.00	0.00	0.00	0.00	
Netherlands	1980–1984 1985–1989 1990–1994	1.71 2.27 4.09	 1.38	0.63 0.88 2.68	0.37 0.39 0.65	 1.95	0.00 0.00 0.01	0.34 0.15 0.19
New Zealand	1980–1984	0.28		0.43	1.50			
Norway	1980–1984 1985–1989 1990–1994	1.21 1.44 2.33	0.51 0.51 0.31	0.85 0.68 0.33	0.70 0.47 0.14	1.67 1.35 1.06	0.00 0.00 0.00	0.04 0.09
Pakistan	1990–1994	0.13	0.12	0.62	4.66	5.00	0.11	0.63
Peru	1990–1994	0.26	0.23	0.4	1.54	1.75	0.01	
Poland	1990–1994	2.25	2.09	3.83	1.71	1.84	0.01	0.15
Portugal	1985–1989	0.63	0.52	0.18	0.28	0.34		
Russian Federation	1985–1989 1990–1994	12.8 2.99	 2.99	104 6.08	8.15 2.03	 2.03	 0.00	 0.04
Slovakia	1990–1994	0.89	0.36	0.91	1.03	2.50	0.00	0.10
Slovenia	1990–1994	0.81	0.58	0.3	0.37	0.52	0.00	0.10
South Africa	1975–1979 1980–1984 1985–1989 1990–1994	2.01 2.90 2.3 0.12	0.79 1.18 0.55 0.08	0.21 2.11 5.71 0.27	0.11 2.11 4.41 2.31	0.27 5.17 10.50 3.60	0.00 0.03 0.00 0.03	0.05 0.41 0.69 0.27
Spain	1985–1989	3.02	2.0	3.98	1.32	1.60	0.01	0.02
Sri Lanka	1990–1994	0.06	0.03	0.04	0.73	1.54	0.01	0.49
Sweden	1990–1994	1.09		0.48	0.44			
Switzerland	1975–1979 1980–1984 1985–1989 1990–1994	11.7 12.9 13.6 2.77	 	10.2 5.92 4.08 0.33	0.87 0.46 0.30 0.12	 	0.01 0.00 0.00 0.00	0.31 0.14 0.08 0.18
Syrian Arab Republic	1990–1994	0.07	0.01	0.02	0.28	2.50	0.00	0.00
Thailand	1990–1994	2.31	0.25	1.81	0.78	7.18	0.02	0.68

Table 24 (continued)

Country / area	*Period*	*Monitored workers* (thousands)	*Measurably exposed workers* (thousands)	*Annual collective effective dose* (man Sv)	*Average annual effective dose (mSv)*		NR_{15} [b]	SR_{15}
					Monitored workers	*Measurably exposed workers*		
USSR	1975–1979	7.78		126	16.2			
	1980–1984	9.85		122	12.4			
	1985–1989	12.8		104	8.15			
United Kingdom	1980–1984	28.0		26.0	0.93			
	1985–1989	18.80	15.1	21	1.12	1.39	0.01	
	1990–1994	19.60	10.27	13.0	0.67	1.27	0.00	
United Rep. Tanzania	1990–1994	0.03	0.02	0.08	2.46	3.56	0.00	0.00
United States [f]		202.00		290	1.44			
	1975–1979	305.00		380	1.25			
	1980–1984	274.00	101	150	0.55	1.49		
	1985–1989	10.04	5.75	25.2	2.51	4.39	0.03	0.34
Reported total [g]	1975–1979	240		445	1.81		0.01	0.36
	1980–1984	386		552	1.43		0.01	0.29
	1985–1989	423		343	0.81		0.01	0.34
	1990–1994	267	69	163	0.61	2.37	0.01	0.26
World estimate [h]	1975–1979	530	290	870	1.64	3.0	0.01	0.35
	1980–1984	690	300	940	1.36	3.2	0.01	0.28
	1989–1989	560	250	510	0.90	2.00	0.01	0.31
	1990–1994	700	160	360	0.51	2.24	0.00	0.25
		(390)	(100)	(240)	(0.62)	(2.34)	(0.01)	(0.26)

a Data are annual averages over the periods indicated.
b The values of NR are for the monitored workforce.
c Includes exposures of workers at the research reactor and in research establishments.
d Within the data from 1990-1994, the data concerning 1990 only relate to the Federal Republic of Germany.
e The reported number of workers is small compared with numbers in comparable industrialized countries, which suggests that the data are incomplete.
f Calculation of SR distribution ratios based on data from 1993 and 1994.
g The total for measurably exposed workers has been rationed up to take account of countries that did not report the number of measurably exposed workers, but did report a figure for monitored workers.
h The values shown in brackets are the world estimates based on the standard method given in Section I.E; however, the Committee identified a more robust method of estimation for this instance, based on the regional value for the United States being taken to be equivalent to the rest of the OECD (see para 156). These are the unbracketed figures.

Table 25
Summary of worldwide exposures from industrial uses of radiation [a]

Period	*Monitored workers (thousands)*	*Measurably exposed workers (thousands)* [b]	*Annual average collective effective dose (mSv)*	*Annual average individual dose (mSv)*	
				Monitored workers	*Measurably exposed workers*
Industrial radiography					
1985–1979	72		190	2.6	
1980–1984	120		230	2.0	
1985–1989	110		160	1.44	
1990–1994	106	53	170	1.58	3.17
Radioisotope production					
1985–1979	57		130	2.3	
1980–1984	82		100	1.3	
1985–1989	88		98	1.12	
1990–1994	24	26	47	1.93	2.95
Other [c] [d]					
1985–1979	260		480	1.8	
1980–1984	310		570	1.8	
1985–1989	200		230	1.1	
1990–1994	570		140	0.25	
All industry [d]					
1985–1979	390		800	2.05	
1980–1984	510		900	1.76	
1985–1989	400		490	1.23	
1990–1994 [e]	700	160	360	0.51	2.24
	(390)	(100)	(240)	(0.62)	(2.34)

a The data are annual values averaged over the respective five year periods and are in general quoted to two significant figures.
b The total for measurably exposed workers has been rationed up to take account of countries that did not report the number of measurably exposed workers, but did report a figure for monitored workers.
c Estimated by subtracting the contributions from the specified practices from the estimated value for all industry.
d The "All industry" data in previous reports included "Tertiary education and research institutes". The figures quoted in this document for the previous periods are with this component removed to permit a better comparison with the data for 1990–1994.
e The values shown in brackets are the world estimates based on the standard method given in Section I.E; however the Committee identified a more robust method of estimation for this instance, based on the regional value for the United States being taken to be equivalent to the rest of OECD (see para 156).

Table 26
Exposures to workers involved in industrial radiography in the United Kingdom
[H1, H2]

Year	*Numbers of workers in dose range*				*Total number of workers with dose > 5 mSv*	*Annual collective dose (man Sv)*	*Average annual dose (mSv)*	
	5–10 mSv	*10–15 mSv*	*15–20 mSv*	*>20 Sv*			*To all workers*	*To workers with non–zero doses*
1986	170	75	15	42	302	7.5	1.4	1.8
1987	125	52	24	25	226	6	1.0	1.5
1988	107	27	7	15	156	3.7	0.7	1.4
1989	89	39	18	24	170	4.8	0.8	1.9
1990	97	37	14	21	169	4.0	0.7	1.3
1991	120	32	26	24	202	4.6	0.9	1.7
1992	97	29	7	16	149	4.9	0.9	1.8
1993	79	23	8	18	128	3.0	0.6	1.5
1994	53	25	17	14	109	2.7	0.6	1.3
1995	56	12	5	11	84	2.4	0.6	1.4
1996	62	19	3	6	90	2.4	0.6	1.6

Table 27
Worldwide exposure from all industrial uses of radiation [a]

Region	*Monitored workers* (thousands)	*Measurably exposed workers* (thousands)	*Average annual collective dose* (man Sv)	*Average annual individual dose (mSv)*		*Collective effective dose* [b] *per unit GDP* (man Sv per 10^{12} US$)
				Monitored workers	*Measurably exposed workers*	
1975–1979						
East and South-East Asia [c]						
Eastern Europe [d]	17		176	10		150
Latin America						
OECD except United States [e]	210		240	1.1		79
United States (estimate)	200		290	1.4		150
Remainder [f]	100		170	1.7		120
Total	530		870	1.6		120
1980–1984						
East and South-East Asia	12		9	0.79		20
Eastern Europe [c]	20		150	7.9		68
Latin America						
OECD except United States [e]	240		240	0.99		49
United States (estimate)	310		380	1.3		110
Remainder [f]	110		160	1.4		73
Total	690		940	1.4		72
1985–1989						
East and South-East Asia [c]	10		7	0.65		13
Eastern Europe [d]	26		140	5.6		41
Latin America	24		43	1.8		52
OECD except United States [e]	180		130	0.69		16
United States (estimate)	270		150	0.55		31
Remainder [f]	41		35	0.85		26
Total	560		510	0.9		26
1990–1994						
East and South-East Asia	21	11	18	0.86	1.61	16
Eastern Europe	23	16	29	1.24	1.85	16
Indian subcontinent	7	4	12	1.64	2.92	24
Latin America	4	2	4	1.18	2.27	5
OECD except United States	320	62	140	0.44	2.27	12
United States [g]	320	62	140			
	(10)	(6)	(25)	(2.51)	(4.39)	(5)
Remainder	4	1	10	2.58	7.87	7
World [g]	700	161	510	0.51	2.24	34
	(390)	(69)	(360)	(0.62)	(2.34)	(31)

a The data are annual averages over the respective five year periods and are, in general, quoted to two significant figures.

b The normalized collective doses per unit GDP for the three five year periods are expressed, respectively, in terms of 1977, 1983, 1989 and 1994 prices; direct comparison between the values for different periods is possible only after correcting for these different price bases.

c Non-centrally planned economies in East- and South-East Asia.

d Including the whole of the former USSR.

e All countries are members of the Organization for Economics Co-operation and Development (OECD) except for the United States.

f Includes the remainder of the world for which values are not specifically tabulated elsewhere in the Table. Note that the countries or regions comprising the remainder differ in the respective five year periods.

g The values shown in brackets are the world estimates based on the standard method given in Section I.E; however the Committee identified a more robust method of estimation for this instance, based on the regional value for the United States being taken to be equivalent to the rest of OECD (see para 156).

Table 28
Estimates of effective dose from cosmic radiation for typical flight routes
[E2]

Route	*Flight duration (min)*	*Effective dose (mSv)*	
		One flight on route	*1,000 hours flying on route*
Short-haul routes			
Dublin – Paris	95	0.0045	2.8
London– Rome	135	0.0067	3.0
Frankfurt – Helsinki	160	0.0100	3.7
Brussels – Athens	195	0.0098	3.0
Luxembourg – Madrid	130	0.0054	2.6
Stockholm – Vienna	140	0.0082	3.5
Lisbon – Munich	180	0.0091	3.0
Copenhagen – Dublin	120	0.0071	3.5
Amsterdam – Manchester	70	0.0030	2.6
Dublin – Rome	180	0.010	3.3
Long-haul routes			
Stockholm – Tokyo	605	0.051	5.0
Dublin – New York	450	0.046	6.1
Paris – Rio de Janeiro	675	0.026	2.3
Frankfurt – Bangkok	630	0.030	2.9
London – Toronto	490	0.050	6.2
Amsterdam – Vancouver	645	0.070	6.6
Los Angeles – Auckland	760	0.030	2.3
London – Johannesburg	655	0.025	2.3
Perth – Harare	665	0.039	3.5
Brussels – Singapore	675	0.030	2.7

Table 29
Reported exposures to workers from natural sources of radiation
Data from UNSCEAR Survey of Occupational Exposures

Country / area	Period	Monitored workers (thousands)	Measurably exposed workers (thousands)	Annual collective effective dose (man Sv)	Average annual effective dose (mSv)		Distribution ratio (number of workers)				Distribution ratio (collective dose)			
					Monitored workers	Measurably exposed workers	NR_{15}	NR_{10}	NR_5	NR_1	SR_{15}	SR_{10}	SR_5	SR_1
Civil aviation														
Bulgaria [a]	1990–1994	1.4		5.60	4.00									
Finland	1990–1994	1.93		3.78	1.96									
United Kingdom	1991	24.0		50.0	2.08									
Total	1990–1994	27.3		59.4	2.15									
Coal mining														
Myanmar	1994	< 0.01	< 0.01	0	0.68	0.68	0	0	0	0.50				
United Kingdom	1991	48.7		28.6	0.59									
Total	1990–1994	48.7		28.6	0.59		0	0	0	0.50				
Other mineral mining														
Australia	1990–1994	0.34	0.26	0.19	0.56	0.73	0	0	0	0.19	0	0.02	0.05	0.70
Finland	1990–1994	0.42		0.54	1.30									
Germany	1990–1994	1.02	1.00	2.35	2.31	2.19	0	0.01	0.09	0.71	0	0.04	.029	0.93
Slovenia [b]	1990–1994	0.18	0.18	6.38	34.7	34.7	0.79	0.84	0.91	0.99				
South Africa	1990–1994	250		640	2.6									
United Kingdom	1991	1.35		6.1	4.53									
Total	1990–1994	3.30		15.6	4.71		0.10	0.11	0.17	0.63	0	0.04	0.27	0.91
Oil and natural gas industries														
Myanmar	1990–1994	0.01	0.01	0	0.66	0.66	0	0	0	0.25				
United Kingdom	1990–1994	0.58	0.21	0.12	0.21	0.59	0	0	0.01	0.03				
Total	1990–1994	0.59		0.12	0.21		0	0	0.01	0.03				
Handling of minerals and ores														
South Africa	1990–1994	2.37	2.37	2.58	1.09	1.09	0	0	0.02	0.10	0	0.02	0.14	0.29

a Number of monitored workers is estimated. The assessment of dose is based on 400 flight hours and a mean dose rate. The radiation weighting factor for neutrons is taken to be 15.
b Reported data relate to workers in lead and zinc mines.

Table 30
Employment in underground mining worldwide in 1991
[C4]

Country	*Number of miners (thousands)*		
	Coal mining	*Other mining*	*Total*
China [a]	1 594	64	1 658
Czechoslovakia	55	2	57
Germany	105	4	109
India	669	10	679
Poland	251	10	261
South Africa	46	340	386
Spain	38	4	42
USSR	840	40	880
United Kingdom	46	2	48
United States	51	15	66
Other countries	213	265	478
Total	3 908	756	4 664

a The Chinese data for coal mining represent large and intermediate mines only, which produce about 60% of the coal.

Table 31
Exposures to radon and decay products in non-uranium mines

Country	*Year*	*Coal mining*			*Other mining*			*Ref.*
		Number of mines	*Annual exposure (mSv)*	*Exposure above 10 mSv (%)*	*Number of mines*	*Annual exposure (mSv)*	*Exposure above 10 mSv (%)*	
Australia	1991	3	1.0	0	23	0.5	0	[H10]
Canada	1980s				4	2.0	2	[A2]
France	1981	3	1.0	0	5	5.0	8	[B6]
Germany	1990	20	0.5	0				[R3]
	1991				45	7.0	18	[S6]
India	1980s	5	0.1	0				[M3]
	1980s				22	4.0	9	[N7]
Italy	1970s				35	6.0	8	[S7]
Poland	1980s	71	1.5	0.2	26	0.5	0	[D6]
South Africa	1970s				25	3.5	10	[G4]
	1993				40	1.8	0	[W4]
USSR		47	0.2		26	4.3		[P3]
United Kingdom	1980s	220	0.5	0				[D7]
	1990				41	2.3	7	[B7]
United States	1975	223	0.5	< 1	10	2.5	4	[R4]
	1990				99 [a]	6.0		[B8]
	1985				86 [b]	0.6		[E4]
Yugoslavia	1970s	5	1.0	0				[K3]
	1980s				2	8.5	50	[K3]

a Metal mines.
b Non-metal mines.

Table 32
Worldwide collective dose from inhalation of radon and its decay products from underground mining (excluding uranium) in the years 1990–1994

Country	*Number of miners* [a]	*Exposure to radon progeny* [b]	
		Annual collective effective dose (man Sv)	*Average annual effective dose (mSv)*
Coal mines			
Germany	105	53	0.50
India	669	67	0.10
Poland	251	380	1.50
USSR	840	170	0.20
United Kingdom	46	23	0.50
United States	51	26	0.50
Other	1 940	690	0.36
Total	3 910	1 410	0.36
Other mines (excluding uranium) [c]			
Germany	4	28	7.0
India	10	40	4.0
Poland	10	5	0.5
South Africa [d]	340	610	1.8
USSR	40	170	4.3
United Kingdom	2	5	2.3
United States	48 [e]	210	4.4
Other	306	750	2.4
Total [f]	760	1 820	2.4
All underground mines (excluding uranium mines)			
World	4 670	3 230	0.7

a Unless otherwise indicated, number of miners is taken from Table 30. In the category "Other mines" the number of miners also include uranium miners; corrections are made for this in the totals.
b Derived from reported exposures in Table 31 assuming a conversion factor of 5.0 mSv WLM^{-1}.
c The number of miners include those working in uranium mines and the estimated collective doses are, therefore, overestimates; this is corrected in the total collective dose but not on a country by country basis. The reported average individual doses are averages over all underground mines excluding coal and uranium mines.
d Exposure data taken from [W4] which are representative for the 1990s; somewhat higher levels were reported in the 1970s [G4] (see Table 31).
e Value taken from [E4]; it is for all underground miners in the United States except those working in coal and uranium mines.
f Uranium miners have been excluded from the total.

Table 33
Natural radionuclides in minerals and ores

Material	*Typical concentration in ore/raw material (kBq kg^{-1})*		*Typical concentration in tailings/wastes (kBq kg^{-1})*
	Uranium	*Thorium*	*^{226}Ra*
Bastnaesite		5	
Bauxite, red mud	<1	<1	<1
Fluorspar			4
Ilmenite and rutile	<1	<1	
Monazite	6–20	4% (by weight)	
Oil, natural gas			<4 000 (in scales in pipes)
Phosphate	0.1–4		<1 (in phosphogypsum wastes)
Pyrochlore and columbite	50	50	
Tin	<1	<1	
Zirconium (baddeleyite and zircon)	<5	<1	

Table 34
Minerals recovered in mining and processing of mineral sands in Western Australia
[K1]

Mineral	*Chemical formula*	*Percentage of production*	*Concentration (% by weight)* [a]	
			Thorium	*Uranium*
Ilmenite	$FeOTiO_2$	76	0.005–0.05	0.001–0.003
Monazite	$[Ce,La,Nd,Th]PO_4$	<1	5–7	0.1–0.5
Rutile	TiO_2	<5	0.005–0.01	0.001–0.003
Zircon	$ZrSiO_4$	19	0.01–0.025	0.015–0.03
Xenotine	YPO_4	<1	1.5	0.4

a 10^{-4}% (1 ppm) = 4.1 Bq kg^{-1} ^{232}Th and 12.5 Bq kg^{-1} ^{238}U. These data were erroneously converted and included in the UNSCEAR 1993 Report [U3].

Table 35
Summary of occupational exposures to natural radiation excluding uranium mining

Occupation or practice	*Number of workers (thousands)*	*Worldwide annual collective effective dose (man Sv)*	*Average annual effective dose (mSv)*
Coal mining [a]	3 910	2 600	0.7
Other mining [a]	760	2 000	2.7
Mineral processing, etc. [b]	300	300	1.0
Exposure above ground (radon) [c]	1 250	6 000	4.8
Aircrew	250	800	3.0
Total	6 500	11 700	1.8

a These estimates have been derived from the estimates for inhalation of radon and its progeny with corrections for the addition of 0.8 mSv per worker for naturally occurring external exposure and the reduction by 0.5 mSv per worker to account for the dose that the person would receive irrespective of work.

b Includes coal-fired power plants and extraction of mineral sands, phosphate ores and their subsequent use.

c A crude estimate extrapolated by GDP from an estimate of 240 man Sv in the United Kingdom arising from exposure inhalation of radon and its decay products in places of work above an action level.

Table 36
Exposures to workers in defence activities related to nuclear weapons in the United States
[D4]

Year	*Workers in workforce*	*Monitored workers*	*Measurably exposed workers*	*Average dose [a] (mSv)*	*Collective effective dose equivalent (man Sv)*			
					External photon	*External neutron*	*Internal*	*Total*
1990	177 313	108 065	36 074	0.85	18.5	3.8	8.2	30.5
1991	183 546	119 770	31 326	0.82	14.2	3.4	8.1	25.7
1992	191 036	123 711	29 414	0.78	11.9	3.1	7.9	23.0
1993	194 547	127 042	24 049	0.68	12.0	3.3	0.95	16.3
1994	184 073	116 511	25 390	0.65	12.7	3.3	0.43	16.4
1995	172 178	127 276	23 613	0.78	14.4	3.7	0.31	18.4

a To measurably exposed workers.

Table 37
Exposures to workers involved in defence activities in the United Kingdom
[H3, H9]

Year	*Number of workers*	*Percentage of workers in dose range*						*Average annual dose (mSv)*	*Annual collective dose (man Sv)*
		0–5 mSv	*5–10 mSv*	*10–15 mSv*	*15–20 mSv*	*20–30 mSv*	*>30 mSv*		
Nuclear weapons fabrication									
1990	3 935	98.9	0.9	0.1	0.00 [a]			0.4	1.7
1991	4 031	99.2	0.7	0.1	0.00 [a]			0.3	1.2
1992	4 153	99.2	0.8	0.00	0.00	0.00	0.00	0.3	1.1
1993	4 259	99.5	0.5	0.00	0.00	0.00	0.00	0.2	1.0
1994	4 320	99.9	0.1	0.00	0.00	0.00	0.00	0.2	0.8
Nuclear-powered ships and support facilities									
1990	8 516	92.8	4.8	1.5	0.5	0.4	0.01	1.3	11.1
1991	8 534	96.0	3.9	1.0	0.08	0.05	0.01	1.0	8.6
1992	10 861	97.8	1.97	0.16	0.00	0.018	0.028	0.7	7.3
1993	10 391	98.2	1.57	0.21	0.00	0.0	0.0	0.7	7.0
1994	10 596	99.1	0.75	0.16	0.00	0.0	0.0	0.6	6.2

a Above 15 mSv.

Table 38
Exposure to workers from defence activities [a]
Data from UNSCEAR Survey of Occupational Exposures

Country	*Period*	*Monitored workers*	*Measurably exposed workers*	*Annual collective effective dose (man Sv)*	*Average annual effective dose (mSv)*		*Distribution ratio (number of workers)*				*Distribution ratio (collective dose)*			
					Monitored workers	*Measurably exposed workers*	NR_{15}	NR_{10}	NR_5	NR_1	SR_{15}	SR_{10}	SR_5	SR_1
Weapons fabrication and associated activities														
United Kingdom [b]	1975–1979 [c]	3.14		2.95	0.94		0.00				0.00			
	1980–1984	3.71		3.56	0.96		0.00				0.00			
	1985–1989	4.20		2.46	0.59		0.00				0.00			
	1990–1994	4.14		1.16	0.28		0.00				0.00			
United States [d]	1975–1979	17.6	9.31	10.9	0.62									
	1980–1984	18.3	8.26	11.7	0.62									
	1985–1989	15.9	7.54	11.9	0.75									
	1990–1994	20.8	7.6	5.9	0.28									
Total [e]	1975–1979	20.8		13.8	0.67									
	1980–1984	22.5		15.2	0.68									
	1985–1989	20.1		14.4	0.71									
	1990–1994 [f]	24.9		7.1	0.28									
Nuclear ships and their support facilities														
United Kingdom [g]	1975–1979 [d]	6.36		26.3	4.13		0.071							
	1980–1984	6.43		20.1	3.11		0.050							
	1985–1989	6.24		11.6	1.86		0.019							
	1990–1994	9.78		8.0	0.82		0.00							
United States	1975–1979	35.2		65.9	1.87			0.051						
	1980–1984	45.3		45.8	1.01			0.012						
	1985–1989	56.4		45.6	0.81			0.012						
Total [e]	1975–1979	41.6		92.2	2.22									
	1980–1984	51.8		65.8	1.27									
	1985–1989	62.6		57.3	0.91									
	1990–1994	9.8		8.0	0.82									

Table 38 (continued)

Country	*Period*	*Monitored workers*	*Measurably exposed workers*	*Annual collective effective dose (man Sv)*	*Average annual effective dose (mSv)*		*Distribution ratio (number of workers)*				*Distribution ratio (collective dose)*			
					Monitored workers	*Measurably exposed workers*	NR_{15}	NR_{10}	NR_5	NR_1	SR_{15}	SR_{10}	SR_5	SR_1
All defence activities														
France	1990–1994	5.7	0.73	1.31	0.23	1.78	0.00	0.00	0.01	0.13				
Netherlands	1990–1994	0.15	0.02	<0.01	0.01	0.19	0.00	0.00	0.00	0.00	0.00	0.00	0.00	
United Kingdom	1975–1979 1980–1984 1985–1989 1990–1994	11.9 12.8 12.2 13.9		35.8 26.3 14.6 9.2	3.00 2.06 1.19 0.66		0.04 0.03 0.01 0.00	 0.00	 0.02					
United States	1975–1979 1980–1984 1985–1989 1990–1994	92.5 104 115 119	55.8 61.5 73.0 29.3	101 56 69 22	1.09 0.54 0.60 0.19	1.81 0.91 0.95 0.76								
Total	1975–1979 1980–1984 1985–1989 1990–1994	104 116 127 139		137 82 84 33	1.3 0.71 0.66 0.24									

a The data are annual values over the indicated periods.
b The actual effective doses are typically less than 50% of the tabulated values, which are those measured by the dosimeter.
c The value for this period are averages for the year 1979.
d Includes exposures of employees of the United States Department of Energy and contractors engaged in weapons fabrication and testing. Before 1987 the collective doses were evaluated as the sum of the products of the number of workers and the mean dose in dose interval; subsequently, actual individual doses were used in the summation.
e Values derived as the sum or weighted average of the five-year averaged data for the United Kingdom and the United States.
f The value used is the average for 1992-1994, taken from [D4].
g The data are reported for on-board and shore personnel. Shore-based personnel may compromise both civilian and service personnel. Since the early 1980s, dosimeters have been issued only to on-board personnel who need it during their duties at sea and to those designated as classified persons on shore.

Table 39
Exposures to workers from miscellaneous uses of radiation [a]
Data from UNSCEAR Survey of Occupational Exposures

Country	*Period*	*Monitored workers (thousands)*	*Measurably exposed workers (thousands)*	*Annual collective effective dose (man Sv)*	*Average annual effective dose (mSv)*		*Distribution ratio* [b] *(number of workers)*				*Distribution ratio (collective dose)*			
					Monitored workers	*Measurably exposed workers*	NR_{15}	NR_{10}	NR_5	NR_1	SR_{15}	SR_{10}	SR_5	SR_1
Educational establishments														
Australia [c d]	1975–1979 1985–1989 1990–1994	0.55 2.22 0.62	 0.94 0.21	0.055 0.069 0.02	0.10 0.03 0.04	 0.07 0.11	 0.00 0.00	0.00	0.00	0.00	 0.00 0.00	0.00	0.00	0.23
Brazil [e]	1990–1994	0.94	0.04	0.02	0.03	0.54	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.42
Bulgaria [f]	1992	0.25		0.25	1.00									
Canada [g]	1975–1979 1980–1984 1985–1989 1990–1994	5.01 7.40 9.51 14.7	0.89 1.02 1.62 1.51	0.69 0.80 1.05 0.76	0.14 0.11 0.11 0.05	0.78 0.78 0.65 0.50	0.0005 0.0003 0.0003 0.00	0.00	0.00	0.01	0.090 0.044 0.086 0.03	0.06	0.14	0.44
China, Taiwan Province	1985–1989 1990–1994	0.71 1.10	 0.22	0.04 0.15	0.056 0.14	 0.69	0.00	0.00	0.00	0.02	0.18	0.18	0.23	0.47
Cuba	1990–1994	0.02	0.02	0.03	1.32	1.34	0.00	0.00	0.00	0.50	0.00	0.00	0.00	0.31
Czech Republic [h]	1975–1979 1980–1984 1985–1989 1990–1994	0.08 0.18 0.21 0.86	 0.60	0.04 0.18 0.12 0.57	0.45 0.97 0.56 0.66	 0.93	0.003 0.017 0.001 0.00	0.00	0.01	0.16	0.23 0.58 0.030 0.04	0.06	0.13	0.46
Finland [i]	1980–1984 1985–1989 1990–1994	0.95 1.18 1.33	0.023 0.032 0.08	0.038 0.053 0.22	0.040 0.045 0.17	1.63 1.68 2.79	0.00 0.008 0.00	0.00	0.01	0.03	0.062 0.11 0.21	0.42	0.64	0.92
France	1985–1989	3.8	0.09	0.20	0.053	2.22	0.001							
Germany [j k l]	1975–1979 1980–1984 1985–1989 1990–1994	0.22 0.21 21.31 26.6	0.008 0.003 1.055 0.90	0.022 0.003 1.539 0.88	0.104 0.015 0.116 0.03	2.79 0.93 3.48 0.98	0.0009 0.00 0.0004 0.00	0.00	0.00	0.01	0.19 0.00 0.17 0.08	0.14	0.30	0.70
Greece	1990–1994	0.35	0.02	0.02	0.06	1.19	0.00	0.00	0.00	0.02	0.00	0.00	0.22	0.73

Table 39 (continued)

Country	*Period*	*Monitored workers (thousands)*	*Measurably exposed workers (thousands)*	*Annual collective effective dose (man Sv)*	*Average annual effective dose (mSv)*		*Distribution ratio [b] (number of workers)*				*Distribution ratio (collective dose)*			
					Monitored workers	*Measurably exposed workers*	NR_{15}	NR_{10}	NR_{5}	NR_{1}	SR_{15}	SR_{10}	SR_{5}	SR_{1}
Hungary [m]	1975–1979 1980–1984 1985–1989 1990–1994	0.22 0.21 0.21 0.39	0.008 0.003 0.005 0.01	0.022 0.003 0.009 0.01	0.104 0.015 0.044 0.04	2.79 0.93 2.02 0.95	0.0009 0.00 0.00 0.00	0.00	0.00	0.01	0.19 0.00 0.00 0.00	0.00	0.00	0.62
India [n]	1980–1984 1985–1989 1990–1994	1.01 1.92 2.06	0.17 0.47 0.54	0.29 0.45 0.44	0.29 0.24 0.21	1.74 0.97 0.81	0.003 0.0005 0.00	0.00	0.00	0.05	0.24 0.067 0.07	0.09	0.16	0.59
Indonesia	1980–1984 1985–1989	0.28 0.66	0.19 0.64	0.25 0.48	0.92 0.72	1.33 0.75	0.018 0.003				0.37 0.11			
Italy	1985–1989	0.66	0.085	0.054	0.082	0.634	0.003				0.001			
Japan	1980–1984 1985–1989 1990–1994	21.4 27.6 59.2	0.79 0.69 0.86	0.49 0.46 0.86	0.023 0.017 0.01	0.62 0.67 1.01	0.0002 0.0000 0.00	0.00	0.00	0.00	0.20	0.28	0.40	0.73
Myanmar	1990–1994	0.02	0.02	0.02	1.18	1.18	0.00	0.03	0.04	0.23				
Netherlands	1990–1994	2.10	0.29	0.31	0.15	1.02	0.00	0.00	0.01	0.01	0.52	0.66	0.73	0.82
Norway [o]	1980–1984 1985–1989 1990–1992	0.42 0.45 0.56	0.025 0.029 0.09	0.014 0.026 0.02	0.032 0.057 0.04	0.55 0.90 0.24	0.00 0.001 0.00	0.00	0.00	0.01	0.00 0.48			
Pakistan	1990–1994	0.03	0.02	0.07	2.73	2.94	0.02	0.08	0.18	0.31	0.25	0.52	0.83	0.91
Portugal	1985–1989	0.78	0.37	0.33	0.42	0.88								
Slovakia	1990–1994	0.31	0.12	0.10	0.33	0.96	0.00	0.00	0.00	0.10	0.00	0.00	0.11	0.49
South Africa	1975–1979 1980–1984 1985–1989	0.23 0.36 0.43	0.042 0.091 0.070	0.002 0.47 0.21	0.007 1.29 0.49	0.04 5.12 3.02	0.00 0.020 0.00				0.00 0.45 0.10			
Sri Lanka	1990–1994	0.03	0.03	0.00	0.05	0.53	0.00	0.00	0.00	0.02	0.00	0.00	0.00	0.70
Sweden	1990–1994	2.38		0.12	0.05									
Switzerland [p]	1975–1979 1980–1984 1985–1989 1990–1994	7.44 8.48 8.83 9.44		5.91 3.44 2.88 2.17	0.79 0.41 0.33 0.23		0.007 0.0006 0.0003 0.00	0.00	0.01	0.05	0.02	0.06	0.22	0.61

Table 39 (continued)

Country	*Period*	*Monitored workers (thousands)*	*Measurably exposed workers (thousands)*	*Annual collective effective dose (man Sv)*	*Average annual effective dose (mSv)*		*Distribution ratio [b] (number of workers)*				*Distribution ratio (collective dose)*			
					Monitored workers	*Measurably exposed workers*	NR_{15}	NR_{10}	NR_{5}	NR_{1}	SR_{15}	SR_{10}	SR_{5}	SR_{1}
Syrian Arab Republic	1990–1994	0.23	0.03	0.05	0.20	0.96	0.00	0.00	0.00	0.02	0.00	0.00	0.05	0.45
Thailand	1990–1994	0.56	0.07	0.07	0.12	0.92	0.00	0.00	0.01	0.02	0.25	0.33	0.52	0.85
United Kingdom	1980–1984 1985–1989 1990–1994	12.5 1.17 1.26	 0.49 0.32	1.3 0.38 0.21	0.10 0.32 0.17	 0.78 0.67	0.00 0.002 0.00	 0.00	 0.01	 0.02	0.00			
United Rep. Tanzania	1990–1994	0.02	0.02	0.04	2.14	2.69	0.00	0.00	0.19	0.42	0.00	0.00	0.54	0.87
United States [q]	1975–1979 1980–1984 1985–1989	0.02 0.03 0.02		18 15 6	0.72 0.58 0.35	 0.86								
Total [r]	1975–1979 1980–1984 1985–1989 1990–1994	38.6 66.0 85.7 125.4	 6.58	23.5 20.4 13.6 7.41	0.61 0.31 0.16 0.06	 1.13	0.004 0.0007 0.0004 0.00	 0.00	 0.00	 0.01	0.19 0.11 0.072 0.09	 0.15	 0.28	 0.62
World [s]	1975–1979 1980–1984 1985–1989 1990–1994	140 180 160 310	 30.0	74 43 22 33	0.55 0.24 0.14 0.11	 1.10	 0.00	 0.00	 0.00	 0.02	 0.07	 0.11	 0.22	 0.55
Veterinary medicine														
Australia [c d]	1975–1979 1985–1989 1990–1994	0.39 2.07 2.66	 0.89 0.88	0.055 0.02 0.07	0.14 0.01 0.03	 0.02 0.07	0.00 0.00 0.00	 0.00	 0.00	 0.00	0.00 0.00 0.16	 0.16	 0.16	 0.30
Brazil [e]	1990–1994	0.02	0.003	0.00	0.25	1.39	0.00	0.00	0.00	0.08	0.00	0.00	0.00	0.78
Canada	1975–1979 1980–1984 1985–1989 1990–1994	0.77 1.27 1.52 2.14	0.24 0.22 0.31 0.29	0.17 0.16 0.17 0.13	0.22 0.13 0.11 0.06	0.73 0.74 0.56 0.46	0.0008 0.0002 0.00	 0.00	 0.00	 0.01	0.11 0.026 0.00	 0.02	 0.05	 0.38
Cyprus	1990–1994	0.002	0.002	0.00	0.70	0.88	0.00	0.00	0.00	0.30	0.00	0.00	0.00	0.87
Czech Republic [h]	1975–1979 1980–1984 1985–1989 1990–1994	0.17 0.23 0.25 0.23	 0.18	0.10 0.14 0.13 0.18	0.59 0.62 0.52 0.75	 0.97	 0.00	 0.00	 0.00	 0.17	 0.00	 0.00	 0.00	 0.37

Table 39 (continued)

Country	*Period*	*Monitored workers (thousands)*	*Measurably exposed workers (thousands)*	*Annual collective effective dose (man Sv)*	*Average annual effective dose (mSv)*		*Distribution ratio [b] (number of workers)*				*Distribution ratio (collective dose)*			
					Monitored workers	*Measurably exposed workers*	NR_{15}	NR_{10}	NR_{5}	NR_{1}	SR_{15}	SR_{10}	SR_{5}	SR_{1}
Denmark	1975–1979 1980–1984 1985–1989 1990–1994	0.49 0.52 0.71 0.94	 0.06	0.022 0.030 0.024 0.02	0.045 0.059 0.034 0.02	 0.37	0.00 0.0004 0.00	 0.00	 0.00	 0.00	0.00 0.17 0.00	 0.00	 0.09	 0.55
Finland	1980–1984 1985–1989 1990–1994	 0.19	0.010 0.02 0.04	0.012 0.03 0.06	 0.29	1.20 1.20 1.50	 0.00	 0.00	 0.01	 0.09	0.00 0.00	 0.00	 0.30	 0.84
France [t]	1985–1989	1.19	0.09	0.02	0.17	2.30	0.00							
Hungary	1975–1979 1980–1984 1985–1989 1990–1994	0.081 0.14 0.06	0.009 0.01 0.004	0.045 0.03 0.01	0.55 0.20 0.10	5.07 2.78 1.56	0.010 0.00 0.00	 0.00	 0.00	 0.03	0.42 0.24 0.00	 0.00	 0.16	 0.74
Iceland	1990–1994	0.01	0.00		0.00		0.00	0.00	0.00	0.00				
India	1975–1979 1980–1984 1985–1989	0.062 0.080 0.09	0.021 0.026 0.03	0.011 0.16 0.02	0.17 0.20 0.20	0.51 0.61 0.53	0.00 0.00 0.00				0.00 0.00 0.20			
Ireland	1985–1989	0.04	0.002	0.00	0.02	0.33								
Japan [u]	1985–1989 1990–1994	18.0 1.38	 0.20	1.4 0.15	0.08 0.11	 0.71	 0.00	 0.00	 0.00	 0.02				
Myanmar	1990–1994	0.004	0.004	0.00	0.61	0.61	0.00	0.00	0.00	0.00				
Netherlands	1990–1993	1.16	0.57	0.53	0.45	0.92	0.00	0.01	0.02	0.12	0.14	0.25	0.42	0.77
Slovakia	1990–1994	0.08	0.01	0.01	0.14	1.14	0.00	0.00	0.00	0.04	0.00	0.00	0.00	0.61
Slovenia	1990–1994	0.008	0.008	0.01	0.76	0.76	0.00	0.00	0.00	0.05				
South Africa	1975–1979 1980–1984 1985–1989 1990–1994	0.42 0.61 0.75 0.75	0.28 0.20 0.13 0.13	0.013 0.12 0.24 0.24	0.032 0.20 0.32 0.32	0.048 0.60 1.89 0.89	0.001 0.001 0.001 0.00				0.42 0.056 0.068 0.07			
Sweden	1992–1994	0.68		0.08	0.12									

Table 39 (continued)

Country	*Period*	*Monitored workers (thousands)*	*Measurably exposed workers (thousands)*	*Annual collective effective dose (man Sv)*	*Average annual effective dose (mSv)*		*Distribution ratio [b] (number of workers)*				*Distribution ratio (collective dose)*			
					Monitored workers	*Measurably exposed workers*	NR_{15}	NR_{10}	NR_5	NR_1	SR_{15}	SR_{10}	SR_5	SR_1
Switzerland	1975–1979	0.44		0.12	0.27		0.0006				0.032			
	1980–1984	0.59		0.13	0.22		0.00				0.00			
	1985–1989	1.03		0.05	0.05									
	1990–1994	1.39		0.07	0.05		0.00	0.00	0.00	0.01	0.00	0.00	0.11	0.56
United Kingdom	1985–1989	4.00		0.4	0.1									
	1990–1994	0.30	0.08	0.02	0.06	0.21	0.00	0.00	0.00	0.00				
United States [v]	1975–1979	18.1	6.2	14	0.77	2.26								
	1980–1984	21	12	13	0.62	1.08								
	1985–1989	85.0	38.0	36	0.42	0.95								
	1990–1994													
Total reported data [r]	1975–1979	19.7		14.4	0.73		0.001				0.12			
	1980–1984	23.8		13.5	0.57		0.0002				0.027			
	1985–1989	96.4		37.1	0.39		0.00				0.02			
	1990–1994	11.26	2.84	1.34	0.12	0.47	0.00	0.00	0.00	0.03	0.08	0.13	0.24	0.60
World [s]	1975–1979	48		25	0.52									
	1980–1984	65		26	0.40									
	1985–1989	160.0		52	0.32									
	1990–1994	45.0	13.0	8	0.18	0.62	0.00	0.00	0.00	0.03	0.02	0.13	0.24	0.60
Other occupational groups														
Brazil [e]	1990–1994	0.39	0.06	0.30	0.78	4.96	0.01	0.01	0.02	0.06	0.72	0.76	0.84	0.95
China, Taiwan Province	1990–1994	1.99	0.68	1.02	0.51	1.49								
Cuba	1991–1994	0.16	0.15	0.12	0.74	0.74	0.00	0.00	0.00	0.23	0.00	0.00	0.01	0.48
Cyprus	1990–1994	0.01	0.009	0.01	0.61	0.94	0.00	0.00	0.00	0.25	0.00	0.00	0.00	0.77
Czech Republic	1991–1994	0.66	0.47	0.47	0.71	1.00	0.00	0.01	0.02	0.13	0.04	0.13	0.30	0.58
Denmark	1990–1994	0.19	0.002	0.00	0.00	0.00	0.00	0.00	0.00	0.00				
Ecuador	1993–1994	0.05	0.05	0.06	1.04	1.05	0.00	0.00	0.00	0.50				
France	1990–1994	0.84	0.54	3.46	4.10	6.36	0.07	0.13	0.28	0.64				
Germany [j]	1990–1994	3.63	1.14	2.32	0.64	2.03	0.00	0.01	0.03	0.16	0.12	0.21	0.44	0.90
Greece	1990–1994	0.25	0.03	0.07	0.29	2.42	0.00	0.00	0.1	0.06	0.27	0.34	0.53	0.89
Netherlands	1990–1993	0.25	0.01	0.02	0.09	1.84	0.00	0.00	0.00	0.01	0.71	0.71	0.71	0.88
Peru	1994	0.04	0.04	0.02	0.60	0.60	0.00	0.00	0.00	0.23				
Slovakia	1990–1994	0.25	0.12	0.14	0.57	1.18	0.00	0.00	0.00	0.18	0.00	0.00	0.01	0.67
Slovenia	1990–1994	0.06	0.06	1.15	17.7	17.7	0.60	0.75	0.91	0.94	0.88	0.99	1.00	1.00
United States	1990–1994	0.58	0.14	0.40	0.70	0.95	0.00	0.02	0.04	0.12	0.17	0.52	0.77	0.95
Total	1990–1994	9.37		9.56	1.03		0.02	0.03	0.06	0.20	0.33	0.42	0.57	0.88

Table 39 (continued)

a The data are annual values averaged over the indicated periods. They were derived as averages over the years for which data were reported; in some cases, data were reported for only a limited number of years in the periods of interest here.
b The values of NR_{15} are now for the monitored workforce. Values for the exposed workforce can also be estimated where data are given for both monitored and measurably exposed workers.
c For 1975–1989; numbers of workers and the collective doses reported in questionnaire for about 70% of the exposed workforce have been extrapolated for entire country.
d The method of dose recording was different in the two periods for which data are reported, and this may partly account for the differences in data. Average individual doses for 1975–1979 were calculated from the total of the reported doses for an occupational category divided by the estimated number of workers in that category with the results rounded to the nearest 0.1 mSv. In 1990 the estimates were based directly on the results of individual monitoring; in the absence of data for 1985–1989, the data for 1990 have been assumed to be representative of this period.
e Reported data are based on a sample of approximately 25% of monitored workers.
f Reported data contain a contribution from veterinary medicine.
g Data are mainly from universities but exclude exposures at accelerators and in teaching establishments where little research is undertaken.
h Data for 1975–1989 relate to the former Czechoslovakia.
i Includes all research institutes except research reactors and accelerators. No data are available on exposures in tertiary education.
j Within the data from 1990–1994, the data concerning 1990 only relate to Federal Republic of Germany.
k For 1976–1980, the data are for all universities and technical colleges in the non–medical field. For 1981–1989, the data are for all research and education except for that associated with medical and nuclear sciences.
l Data include exposures arising in research and training in natural sciences and technology, including research centres.
m Includes technological education only (i.e. not medicine, science, philosophy etc).
n Includes data from education and research institutes.
o 1980–1989 data are solely for the University of Oslo.
p Data may include some data on research for the nuclear fuel cycle.
q Data are for licensees of the United States Nuclear Regulatory Commission only.
r These data should be interpreted with care, particularly because the countries included in the summations for the respective five–year periods may not be the same, depending on whether data were reported for the period in question. Consequently, direct comparisons of data for different periods is invalid to the extent that the data comprise contributions from different countries. It should also be noted that the data on NR and SR are averages of data reported on these ratios. In general, these data are less complete than those that form the basis of number of workers and collective doses.
s The estimates are extrapolations of regional values based on the gross national product (GDP); because of insufficient data, the estimates of NR and SR are averages of reported data, but these may be considered representative for worldwide exposure.
t The number of workers and the collective dose have been scaled up by a factor of 1.33, since the reported data only covered 75% of those monitored.
u For 1985–1989 the data is for holding assistants; 1.06 man Sv of the collective dose arose in radiographic examinations and 0.34 man Sv in fluoroscopy. Some 2.4 million radiographs were taken with about 5% on large animals with remainder on small animals.
v The values for 1985 (the period 1985–1989) are based on extrapolation of earlier data.

Table 40
Accidents with clinical consequences to occupationally exposed workers
Data from UNSCEAR Survey of Occupational Exposures unless otherwise specified

Country / location	*Year of accident*	*Type of installation or operation*	*Main cause of exposure*	*Persons affected*	*Nature of exposure and health consequences*
Nuclear fuel cycle					
Argentina Atucha	1977	Nuclear reactor	Worker not wearing lead gloves; contamination of a cut caused by edge of the manway plug	1	Wound contaminated with 3,800 Bq (surgical removal of a contaminant); mean beta dose 364 Gy in period 1977–1985 and annual gamma dose of 0.04 in 1 cm^3 of soft tissue; no deterministic effects observed
Argentina Buenos Aires	1983	Critical facility	Failure to follow procedures in removing water from tank containing fissile material	1	Acute whole-body dose of 43 Gy (23 Gy neutron and 21 Gy gamma); death by acute radiation syndrome (neurological) with radiopneumonitis in right lung
France [a]	1979	Nuclear power plant		1	Whole-body dose of 0.34 Gy
German Democratic Rep. Rossendorf	1975	Research reactor	Neutron activation of a sample grossly underestimated	1	Dose of 20–30 Gy to right hand; acute and chronic radiodermatitis (2nd and 3rd degree) and oedema
Hungary Paks	1989	Reactor maintenance	Careless handling of detectors from reactor vessel	1	Whole-body dose of 29 mGy; 1 Gy to fingers on the left hand; temporary increase in temperature in left hand; slight increase in chromosomal aberrations
Sweden Nykoping	1978	Research reactor	Instructions for work not followed	1	Dose of 30 Gy to skin of hand; radiation burn to skin
USSR Chernobyl	1986	Reactor accident	Breach of operating rules	237	Whole-body doses of 1–16 Gy and localized doses to skin; 30 deaths; medical treatment including bone marrow transplants
United States Hanford	1976		Intake of ^{241}Am	1	Dose to bone of 8.6 Gy
United Kingdom [b]	1976		Contamination of both hands and feet from mainly beta-emitting radionuclides	1	Skin dose estimated to be about 1.5 Gy; no clinical effects reported
Industrial uses of radiation					
Argentina La Plata, B.A.	1977	X-ray crystallography	Shutter removed from crystallography set	3	Dose of 10 Gy to hands of one operator (radiation burns); doses to other not quoted
Argentina Buenos Aires	1978	^{192}Ir industrial source	Manual handling of source	1	Dose of 12–16 Gy causing radiation burns to two fingers on left hand
Argentina Buenos Aires	1981	^{192}Ir industrial source	Source became detached and lodged in the delivery tube	2	Doses not quoted; radiation burns on finger tips
Argentina Mendoza	1984	^{192}Ir industrial source	Operator pushed source into camera using a finger	1	Dose of 18 Gy to finger (radiation burn on finger) and of 0.l1 Gy to the whole body

Table 40 (continued)

Country / location	*Year of accident*	*Type of installation or operation*	*Main cause of exposure*	*Persons affected*	*Nature of exposure and health consequences*
Bangladesh [a]	1989	^{192}Ir industrial source		1	Whole-body dose of 2.3 Gy
Belarus Nesvizh	1991	^{60}Co irradiation facility	Improper entry with source exposed	1	11 Gy whole body; death in 113 days
China [c] Shanghai	1980	^{60}Co irradiation facility	Entry into the irradiation chamber during power failure and with defective interlocks	1	Whole-body dose of 5 Gy and localized exposure
China Kaifeng City	1986	^{60}Co source	Accidental exposure for about 3 minutes	2	Whole-body doses of 2.6 and 3.5 Gy; haemopoietic type of acute radiation sickness
China Zhengzhou City	1987	^{60}Co irradiation facility	Accidental entry to irradiation room for 10–15 seconds	1	Estimated whole-body dose of 1.35 Gy; anorexia and nausea four hours later; severe damage to haemopoietic system with restoration of WBC was relatively slow
China Zhao Xian	1988	^{60}Co irradiation facility	Accidental entry to irradiation room for about 40 seconds	1	Estimated whole-body dose of 5.2 Gy; acute radiation sickness (bone marrow syndrome); after three years follow-up, condition good
China Beijing	1989	^{60}Co source	Accidental exposure to source for about 4 minutes	2	Whole-body doses of 0.87 and 0.61 Gy; both suffered mild haemopoietic radiation sickness; recovered
China [c]	1989	^{192}Ir radiography source		1	Localized exposure of 18.37 Gy
China Shanghai	1990		Entry into the irradiation chamber during power failure and with defective interlocks	7	The workers received between 2 and 12 Gy: the two who received 11 and 12 Gy died
China	1992	Irradiation facility	Power loss and safety interlocks out of order	4	1 worker with acute radiation syndrome
Czechoslovakia Pardubice	1977	^{192}Ir industrial radiography source	Technical failure of the equipment and improper actions to bring source back under control	1	Whole-body dose of about 5 mSv; data insufficient for estimating local doses; bullous dermatitis of the thumb of the right hand; plastic surgery two years later
Czechoslovakia Sokolov	1979	^{192}Ir industrial radiography source	Technical failure of the equipment and inadequate monitoring during and after work	1	Whole-body dose of about 5 mSv; data insufficient for estimating local doses; bullous dermatitis of the third finger of the left hand and adjacent areas; plastic surgery two years later
Czechoslovakia Prague	1982	^{192}Ir industrial radiography source	Source transport container declared empty on delivery from abroad and handled as if inactive	1	Whole-body dose of about 2 mSv; data insufficient for estimating local doses; bullous dermatitis of thumb of right hand; conservative treatment
Czechoslovakia Petrvald	1985	Dilution, using a needle, of ^{241}Am solution in glove box	Carelessness and inadequate equipment for work with transuranics	1	Intake through wound of 600 Bq of ^{241}Am; surgical excision of wound and administration of DTPA
Czechoslovakia Prague	1988	Manufacturing of foils containing ^{241}Am for use in fire alarms	New rolling method not tested inactively first; poor radiation protection practice	1	Inhalation of 50 kBq of dispersed ^{241}Am; hospitalization and administration of DTPA; no clinical manifestations

Table 40 (continued)

Country / location	*Year of accident*	*Type of installation or operation*	*Main cause of exposure*	*Persons affected*	*Nature of exposure and health consequences*
El Salvador [a]	1989	^{60}Co irradiation facility	Deterioration of safety system and lack of understanding of radiation hazards	3	Whole-body dose of 3–8 Gy; 1 death
France [c] Nancy	1978	X-ray equipment		1	Localized exposure of hand; amputation of finger
France [c] Montpelier	1979	^{192}Ir radiography source		1	Whole-body and localized exposure; amputation of left arm
France Forbach	1991	Irradiation facility	Exposure to accelerator dark current	3	Severe skin lesions to one worker; less serious injury to two others
German Democratic Rep. Freiberg	1979	X-ray fluorescence unit	Carelessness	1	Dose of 10–30 Gy to right hand and whole-body dose of 0.2–0.5 Gy; acute and chronic radiodermatitis (2nd and 3rd degree)
German Democratic Rep. Bohlen	1980	Analytical x-ray unit	Carelessness	1	Dose of 15–30 Sv to left hand; acute and chronic radiodermatitis (2nd and 3rd degree)
German Democratic Rep. Schwarze Pumpe	1983	^{192}Ir industrial source	Technical defect and inappropriate handling	1	Dose to the right hand of about 5 Gy; acute and chronic radiodermatitis (1st degree)
Germany, Federal Rep.	1975	X-ray fluorescence equipment	Carelessness and technical faults during repair	1	Estimated dose of 30 Gy to the fingers; reddening of two fingers after 10 days
Germany, Federal Rep.	1975	Welding seam test of x-ray equipment	Carelessness and technical defects	1	Estimated dose of 2 Gy to the stomach region
Germany, Federal Rep.	1976	X-ray equipment	Inexpert handling of equipment	1	Estimated whole-body dose of 1 Gy; reddening of skin after 24 hours and radiation after-effects
Germany, Federal Rep.	1980	Radiogram unit	Defective equipment	2	Estimated dose of 23 Gy to the hand and an effective dose of 0.2 Sv
Germany, Federal Rep.	1981	X-ray fluorescence equipment	Carelessness	1	Partial body exposure with 20–30 Gy dose to the right thumb; extensive tissue damage developing over several months
Germany, Federal Rep.	1983	X-ray equipment	Defective equipment	1	Partial body exposure to regions of the body of about 6–12 Gy; localized physical changes
Hungary Győr	1977	Industrial defecto-scope	Failure of equipment to withdraw sources into its container	1	Whole-body dose of 1.2 Gy; slight nausea, changes in blood and increased frequency of chromosomal aberrations; observation and sedative therapy
Hungary Tiszafured	1984	^{192}Ir industrial defectoscope	Failure of equipment and careless handling of source	1	Whole-body dose of 46 mGy; 20–30 Gy estimated for fingers of left hand; radiation burns on fingers of left hand; irreversible necrosis at tip of one finger, surgically removed; slight increase in chromosomal aberrations

Table 40 (continued)

Country / location	*Year of accident*	*Type of installation or operation*	*Main cause of exposure*	*Persons affected*	*Nature of exposure and health consequences*
Italy [a] Brescia	1975	^{60}Co industrial radiography source	Lack of safety systems on conveyor entry point	1	Whole-body dose of 10 Gy; haematopoietic syndrome; death after 13 days
Indonesia Badak, East Borneo	1982	^{192}Ir industrial radiography source	Repair of the source by the operator	1	Estimated doses of 0.77 Gy to the whole body, 0.64 Gy to the gonads and 11.7 Gy to the hands; oedema and suppuration of the hands
Indonesia Cirebon, West Java	1987	Industrial radiography x-ray machine	Repair of shutter while machine was in operation	1	Dose to dorsum of one hand in excess of 10 Gy; oedema and suppuration of the affected hand
India Vikhroli, Bombay	1982	^{192}Ir pencil source	Failure of security during transport of source; source lost and found by a railway worker	1	Dose of 1.5–35 Gy to skin in the region of the groin and whole-body dose of 0.4–0.6 Gy; severe radiation burns in pelvic region with excruciating pain
India Mulund, Bombay	1983	^{192}Ir projector	Operation by untrained personnel	1	Dose to the skin of 20 Gy and to the whole body of 0.6 Gy; severe damage to fingers, four of which were amputated
India Visakhapatnam	1985	^{60}Co radiography projector	Violation of safe working practices and lack of maintenance	2	Skin dose of 10–20 Gy to operator and 0.18 Gy to an assistant; damage to fingers, one finger amputated
India Yamunanager	1985	^{192}Ir radiography projector	Violation of safe working practices associated with power failure in the workplace	2	Doses of 8–20 Gy to hands of both operators; damage to fingers; two fingers amputated from each individual
India Hazira, Gujarat	1989	^{192}Ir radiography projector	Failure of safety management and improper maintenance	1	Dose of 10 Gy to fingers and whole-body dose of 0.65 Gy; radiation burns on fingers of both hands; fingers amputated
Iraq [a]	1975	^{192}Ir radiography source		1	Whole-body dose of 0.3 Gy plus localized exposure of hand
Israel Soreq	1990	^{60}Co irradiation facility	Improper entry procedures and maintenance	1	10–20 Gy whole-body dose; died 36 days later
Norway [c] Kjeller	1982	^{60}Co industrial irradiation facility	Failure of safety device and failure to follow procedures	1	Whole-body dose of 22 Gy; death after 13 days
Peru Zona del Oleoducto	1977	^{192}Ir source	Untrained personnel and lack of supervision; equipment neither registered nor authorized	3	Maximum doses of 164 Gy to hands; 0.9 Gy to lens of the eye; 2 Gy to the whole body; amputation of fingers of two people and effects on left hand of one
South Africa Sasolburg, Tranvaal	1977	^{192}Ir industrial radiography source	Faulty operation of pneumatically operated container and monitor; carelessness of operator	1	Whole-body dose 1.16 Gy; amputation of 2 fingers, rib removal and skin grafts
South Africa Witbank, Transvaal	1989	^{192}Ir industrial radiography source	Detached source; negligence of radiographer (source not properly attached) and failure of portable monitor to register detached source	3	Whole-body doses of three workers; 0.78, 0.09 and 0.1 Gy, computed effective dose to the most exposed was 2.25 Sv; most exposed worker: amputation of right leg at the hip after 6 months and amputation of 3 fingers after one year

Table 40 (continued)

Country / location	*Year of accident*	*Type of installation or operation*	*Main cause of exposure*	*Persons affected*	*Nature of exposure and health consequences*
South Africa Sasolburg, Tranvaal	1990	^{60}Co industrial radiography source	Source left behind after radiography work; loss not detected due to inadequate monitoring, source handled by 6 people	6	Cytogenetic analysis indicated that three people received whole-body doses in excess of 0.1 Gy with a maximum of 0.55 Gy; source handled for periods of 5–20 minutes, but local doses could not be estimated with any accuracy; right hand amputated 10 cm above wrist in one case; patches of sensitive skin on fingers of another; blistering of fingers in two other cases
Switzerland	1992	^{192}Ir radiography source	Jammed 700 GBq source released by hand	1	Erythema of fingers: 3.5 to 10 Gy
USSR [a]	1975	^{192}Ir irradiation facility		2	Whole-body doses of 3 and 5 Gy; dose to hands over 30 Gy
USSR [c]	1976	^{60}Co irradiation facility		1	Whole-body dose of 4 Gy; radiation sickness, haematopoietic syndrome
USSR [a]	1980	^{60}Co irradiation facility		1	Dose of 50 Gy to lens of eye
United Kingdom	1977	Filling gaseous tritium light sources	Broken inlet manifold led to the release of escape of 11–15 TBq of tritium	2	Whole-body doses: 0.62 and 0.64 Sv
United Kingdom [b]	1977	^{192}Ir radiography source	Operator working in a confined area held source for 90 seconds while radiographing a weld	1	Cytogenetic dosimetry estimated an equivalent whole-body dose <0.1 Gy; radiation burns on three fingers
United Kingdom [b]	1978	^{192}Ir radiography source	Radiographer deliberately overexposed himself	1	Cytogenetic dosimetry estimated an equivalent whole-body dose of 1.52 Gy; no localized skin reactions
United Kingdom [b]	1983	Gamma radiography source	Inadvertent exposure of radiographer	1	Whole-body dose of 0.56 Gy
United Kingdom	1991	Industrial radiography	Chronic incidents over 14 years	1	30 Gy to fingers, parts of two fingers amputated. Estimated whole-body dose (chronic) of ≥ 10 Gy. Died of acute myeloid leukaemia
United Kingdom	1993	150 kV radiography unit	Improper procedures	1	Erythema of hands leading to necrotic ulceration; estimated acute dose ≥ 30 Gy
United States [c] Pittsburgh	1976	^{192}Ir radiography source		1	Dose of 10 Gy to hand
United States [c] Rockaway	1977	^{60}Co industrial irradiation source		1	Whole-body dose of 2 Gy
United States [c] Monroe	1978	^{192}Ir radiography source		1	Localized exposure of hand; amputation of finger
United States [c] Los Angeles	1979	^{192}Ir radiography source	Source found by worker and put in his pocket for 45 minutes	5	Whole-body exposure of 1 Gy and localized exposures of hand to one person; localized exposure of hands of four others

Table 40 (continued)

Country / location	*Year of accident*	*Type of installation or operation*	*Main cause of exposure*	*Persons affected*	*Nature of exposure and health consequences*
United States [c] Oklahoma	1981	^{192}Ir radiography source		1	Whole-body and localized exposures
United States	1991	Irradiation facility	Exposure to dark current during maintenance	1	55 Gy to fingers, most of which required amputation
Tertiary education and non industrial accelerators					
German Democratic Rep. Halle	1975	X-ray fluorescence unit	Carelessness	1	Dose of 1.2–2 Gy to middle finger of left hand; acute radiodermatitis (1st degree)
German Democratic Rep. Rossendorf	1980	Radiochemical laboratory	Defect in protective glove led to contamination with ^{32}P	1	Dose of 100 Gy to the skin of the left hand; no clinical symptoms
German Democratic Rep. Berlin	1981	Analytical x-ray unit	Carelessness	1	Dose of 5 Gy to the left hand; acute radiodermatitis (1st degree)
German Democratic Rep. Berlin	1982	Analytical x-ray unit	Carelessness	1	Dose of 6–18 Gy to the right forefinger; acute radiodermatitis (2nd degree)
German Democratic Rep. Leipzig	1983	Radiochemical laboratory	Explosion of vial containing a ^{241}Am solution	1	Committed effective dose of 0.076 Gy
German Democratic Rep. Jena	1988	Analytical x-ray unit	Carelessness	1	Dose of 3 Gy to left hand; acute radiodermatitis (1st degree)
German Democratic Rep. Trustetal	1988	Analytical x-ray unit	Technical defect	2	Maximum dose of 4 Gy to the hand of one person; acute radiodermatitis (1st degree) in one person
Germany, Federal Rep.	1979	X-ray equipment	Defective equipment	1	Estimated dose to part of the hand 20 Gy and effective dose of 0.6 mSv
Peru Lima	1984	X-ray diffraction equipment	Fault of supervision, deliberate exposure from lack of knowledge of risk; equipment not registered with authorities	6	Localized doses of 5–40 Gy to fingers; skin burns and blistering leaving residual scar tissue
USSR [a]	1977	Protein accelerator		1	Localized dose of 10–30 Gy to hands
USSR [a]	1978	Electron accelerator		1	Localized dose of 20 Gy to hands
United States [c]	1978	Accelerator		1	Localized exposure of abdomen, hands and thighs
Viet Nam Hanoi	1992	Research accelerator	Improper entry to adjust sample in beam	1	10–15 Gy to hands, fingers and one hand amputated

Table 40 (continued)

Country / location	*Year of accident*	*Type of installation or operation*	*Main cause of exposure*	*Persons affected*	*Nature of exposure and health consequences*
Medical uses of radiation					
Argentina Tucuman	1975	^{60}Co teletherapy	Failure of source's mechanical mechanisms	2	Technician and physician both received high doses to fingers; radiation burns on fingers
Argentina Parana	1979	Diagnostic radiology	Faulty wiring led to emission of x rays when the top of the fluoroscope was open	1	Auxiliary nurse received whole-body dose of 0.94 Gy; slight depression of bone marrow
Argentina La Plata, B.A.	1982	X-ray therapy facility	Operator looked through window while changing x-ray tubes without recognizing system was energized	1	Whole-body dose of 0.12 Gy and dose of 5.8 Gy to lens of eye; cataracts in both eyes
Argentina Buenos Aires	1983	^{60}Co teletherapy	Source jammed during transfer	2	Doses of 0.66 and 0.67 Gy, respectively, to the thorax; slight bone marrow depression
Germany, Federal Rep.	1975	X-ray equipment	Probably carelessness in maintenance	1	Dose in excess of 1 Gy to head and upper torso
Germany, Federal Rep.	1977	^{192}Ir radiogram unit	Defective equipment	1	Estimated dose to hand of about 5 Gy and effective dose of 0.01 mSv; temporary reddening of fingers
India Ludihana	1980	Radiotherapy (telegamma)	Defective equipment (mercury leaked out through shutter)	3 [d]	Doses of 0.25, 0.4 and 0.5 Gy; no adverse health effects observed
United Kingdom [b]	1975	^{60}Co radiotherapy source	Source jammed in an unshielded position during servicing	2	Personal dosimeters recorded doses of 0.52 and 0.4 Sv
United Kingdom [b]	1977	^{125}I	Accidental contamination of laboratory workers	2	Thyroid dose of 1.7 Gy to one person from an intake of about 1 MBq; a low dose to other person
United Kingdom [b]	1982	X-ray radiography	Inadvertent exposure to x rays	1	Personal dosimeter recorded a dose of 0.32 Sv
United Kingdom [b]	1985	^{125}I	Technician cut his finger while wearing a glove contaminated with iodine-125; sucked cut finger, which resulted in an intake of about 740 MBq	1	Thyroid dose of about 400 Gy
United Kingdom [b]	1986	^{60}Co radiotherapy source	Exposure during source changing	1	Dose of 15 Gy to the hand; erythema and blistering appeared two weeks later

a Data from [I22].
b Data comprise a summary of cases of accidental exposure for which chromosome aberration analysis have been undertaken [L7].
c Data from [R3].
d Unclear whether exposed persons were workers or patients.

Table 41
Other accidents of interest with clinical consequences
Data from UNSCEAR Survey of Occupational Exposures

Country / location	*Year of accident*	*Type of installation or operation*	*Main cause of exposure*	*Persons affected*	*Nature of exposure and health consequences*
Algeria	1978	^{192}Ir radiography source	Lost source	1	1 fatality (member of public)
Brazil Goiania	1986	^{137}Cs radiotherapy source	Abandoned source	~300	21 people in excess of 1.0 Gy (up to 7 Gy): 4 died; many with lesions, 249 with internal contamination
China Xinghou	1992	Former ^{60}Co irradiation facility	Farmer working on the site demolishing facility picked up source: it went with him to hospital	14	14 persons were exposed to >0.25 Gy: 3 received doses >8 Gy and died
Estonia Tammiku	1994	Source from part of an irradiator	Abandoned source and poor source security	6	Whole-body exposure up to 4 Gy, variety of localized exposure up to 1,800 Gy; 1 death
France	1995	Density gauge ^{137}Cs	Handled source (7.4 GBq)	1	Erythema of hands
France	1995	^{192}Ir gamma radiography	Direct handling of 1 TBq source	1	Erythema of hands: estimated local dose >30 Gy
Georgia Lilo	1996/7	^{137}Cs Training sources	Improper management (source security) of sources in a training facility	11	Several lesions of varying seriousness; several suffered vomiting
Iran	1996	^{192}Ir radiography	Poor procedures	1	3 Gy whole-body dose, 50 Gy to chest
Japan Tokai Mura	1999	Reprocessing research	Criticality	3	2 fatalities (17 Gy, 8 Gy) and one other with whole-body dose of 3 Gy
Morroco	1978	^{192}Ir radiography source	Lost source	1	8 fatalities in the public
Turkey Instanbul	1993-1998	Medical therapy sources	Poor source security	18	Five persons with acute radiation (up to 3 Gy) syndrome, one with lesions on one hand
Russian Federation Kremler	1997	Nuclear weapons research facility	Criticality accident	1	5-8 Gy whole-body dose; death after 3 days
Thailand Bangkok	2000	^{60}Co radiotherapy sources	Poor source security leading to three old therapy units ending up in a scrapyard	10	Ten persons were hospitalized of which three died

Table 42
Summary from Radiation Emergency Assistance Centre / Training Site (REAC/TS) radiation accident registries [C7]

Type of use	*Number of accidents*
Criticalities	
Critical assemblies	9
Reactors	7
Chemical operations	6
Total	22
Radiation devices	
Sealed sources	202
X-ray devices	78
Accelerators	23
Radar generators	1
Total	305
Radioisotopes	
Transuranics	26
Tritium	2
Fission products	11
Radium spills	1
Diagnosis and therapy	38
Other	6
Total	84
Total of all	411

Table 43
Worldwide occupational exposures (1990–1994)

Practice	*Monitored workers* (thousands)	*Average annual collective effective dose* (man Sv)	*Average annual collective effective dose per unit energy generated* (man Sv per GW a)	*Average annual effective dose (mSv)*		*Distribution ratio*	
				Monitored workers	*Measurably exposed workers*	NR_{15}	SR_{15}
Nuclear fuel cycle							
Mining	69	310	1.72	4.5	5.0	0.10	0.32
Milling	6	20	0.11	3.3		0.00	0.01
Enrichment	13	1	0.02	0.12		0.00	0.00
Fuel fabrication	21	22	0.1	1.03	2.0	0.01	0.11
Reactor operation	530	900	3.9	1.4	2.7	0.00	0.08
Reprocessing	45	67	3.0	1.5	2.8	0.00	0.13
Research	120	90	1.0	0.78	2.5	0.01	0.22
Total	800	1 400	9.8	1.75	3.1	0.00	0.11
Medical uses of radiation							
Diagnostic radiology	950	470		0.50	1.34	0.00	0.19
Dental practice	265	16		0.06	0.89	0.00	0.24
Nuclear medicine	115	90		0.79	1.41	0.00	0.10
Radiotherapy	120	65		0.55	1.33	0.00	0.15
Total [a]	2 320	760		0.33	1.39	0.00	0.14
Industrial uses of radiation							
Radiography	106	170		1.58	3.17	0.01	0.23
Radioisotope production	24	47		1.93	2.95	0.02	0.25
Other	570	140		0.25			
Total [b]	700	360		0.51	2.24	0.00	0.25
Natural radiation							
Coal mining	3 910	2 600		0.7			
Other mining	760	2 000		2.7			
Mineral processing, etc.	300	300		1.0			
Exposure above ground (radon)	1 250	6 000		4.8			
Aircrew	250	800		3.0			
Total	6 500	11 700		1.8			
Defence activities							
Weapons	380	75		0.19			
Nuclear ships and support	40	25		0.82			
Total	420	100		0.24			
Miscellaneous uses of radiation							
Education	310	33		0.11	1.1	0.00	0.07
Veterinary medicine	45	8		0.18	0.62	0.00	0.02
Total	360	40		0.11	1.0	0.00	0.05
Total of all uses							
Man-made	4 600	2 700		0.6	2.0	0.00	0.13
Natural	6 500	11 700		1.8			
Total	11 100	14 400		1.31			

a These totals includes a component from all other medical uses which is not shown separately.
b These totals includes a component from all other industrial uses which is not shown separately.

Table 44
Trends in worldwide occupational exposures from man-made sources of radiation

Source	*Average annual collective effective dose (man Sv)*				*Average annual effective dose (mSv)*				
					Monitored workers				*Measurably exposed workers*
	1975 – 1979	*1980 – 1984*	*1985 – 1989*	*1990 – 1994*	*1975 – 1979*	*1980 – 1984*	*1985 – 1989*	*1990 – 1994*	*1990 –1994*
Nuclear fuel cycle	2 300	3 000	2 500	1 400	4.1	3.7	2.9	1.75	3.1
Defence activities	420	250	250	100	1.3	0.71	0.66	0.24	
Industrial uses of radiation [a]	800	900	490	360	2.1	1.8	1.2	0.51	2.2
Medical uses of radiation	1 000	1 140	1 030	760	0.78	0.60	0.47	0.33	1.4
Education/veterinary [a]	70	40	20	40				0.11	1.0
Total	5 490	5 330	4 290	2 700	1.9	1.4	1.1	0.6	2.0
	Average annual number of monitored workers (thousands)				*Normalized collective effective dose [man Sv (GW a)$^{-1}$]*				
	1975 – 1979	*1980 – 1984*	*1985 – 1989*	*1990 – 1994*	*1975 – 1979*	*1980 – 1984*	*1985 – 1989*	*1990 – 1994*	
Nuclear fuel cycle	560	800	880	800	18 [a]	17 [a]	12 [a]	9.8	
Defence activities	310	350	380	420					
Industrial uses of radiation [a]	390	510	400	700					
Medical uses of radiation	1 280	1 890	2 220	2 320					
Education/veterinary [a]	140	180	160	360					
Total	2 680	3 730	4 040	4 600					
	NR_{15}				SR_{15}				
	1975 – 1979	*1980 – 1984*	*1985 – 1989*	*1990 – 1994*	*1975 – 1979*	*1980 – 1984*	*1985 – 1989*	*1990 – 1994*	
Nuclear fuel cycle	0.20	0.16	0.10	0.01	0.63	0.55	0.42	0.11	
Defence activities									
Industrial uses of radiation [a]	0.010	0.007	0.009	0.00	0.35	0.28	0.31	0.25	
Medical uses of radiation	0.003	0.002	0.009	0.00	0.14	0.10	0.24	0.14	
Education/veterinary [a]				0.00				0.07	
Total	0.051	0.040	0.030	<0.01	0.45	0.40	0.36	0.13	

a For 1975-1989 the data previously reported for education was subsumed into industrial uses of radiation. In this report the figures for 1975–1989 have been adjusted to remove this component from industrial uses to permit better comparisons.

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